State of California
AIR RESOURCES BOARD

STAFF REPORT:
INITIAL STATEMENT OF REASONS FOR PROPOSED RULEMAKING

Malfunction and Diagnostic System Requirements for 2010 and Subsequent Model Year Heavy-Duty Engines (HD OBD)

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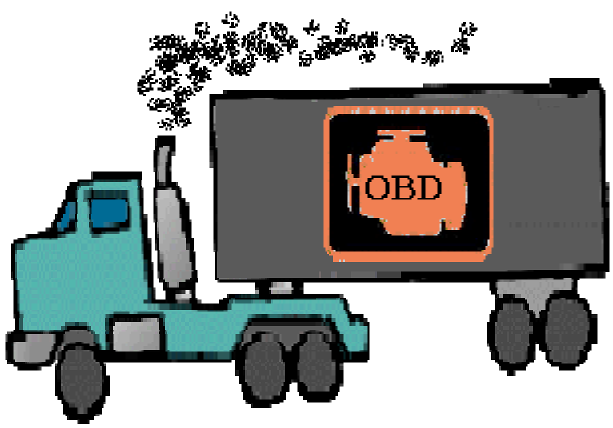

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I. EXECUTIVE SUMMARY

On-board diagnostics (OBD) systems are comprised mainly of software designed into the vehicle's on-board computer to detect emission control system malfunctions as they occur by monitoring virtually every component and system that can cause increases in emissions. When an emission-related malfunction is detected, the OBD system alerts the vehicle owner by illuminating the malfunction indicator light (MIL) on the instrument panel. By alerting the owner of malfunctions as they occur, repairs can be sought promptly, which results in fewer emissions from the vehicle. Additionally, the OBD system stores important information, including identifying the faulty component or system and the nature of the fault, which would allow for quick diagnosis and proper repair of the problem by technicians. This helps owners achieve less expensive repairs and promotes repairs done correctly the first time.

The California Air Resources Board (ARB) originally adopted OBD regulations in 1989 requiring all 1996 and newer model year passenger cars, light-duty trucks, and medium-duty vehicles and engines to be equipped with OBD systems (referred to as OBD II). Only recently had ARB adopted diagnostic requirements to apply to heavy-duty vehicles (i.e., vehicles with a gross vehicle weight rating (GVWR) greater than 14,000 pounds). Specifically, in 2004, ARB adopted the Engine Manufacturer Diagnostic system (EMD) regulation (section 1971, title 13, California Code of Regulations (CCR)), which requires heavy-duty engine manufacturers to implement diagnostic systems on all 2007 and subsequent model year on-road heavy-duty Otto-cycle (gasoline) and diesel engines. However, the EMD regulation is much less comprehensive than the OBD II regulation, requiring the monitoring of a few major emission control technologies and containing no standardized requirements. Essentially, the EMD regulation was developed to require heavy-duty engine manufacturers to achieve a minimum level of diagnostic capability while focusing most of their resources on meeting the new 2007 exhaust emission standards. Thus, as the staff had indicated during the EMD rulemaking, it was the intention of ARB to come back in 2005 and adopt more comprehensive diagnostic, testing, and standardization requirements for future heavy-duty engines.

Consistent with its stated position, ARB staff has developed proposed OBD requirements to phase in beginning with the 2010 model year heavy-duty gasoline and diesel engines (proposed section 1971.1, title 13, CCR, which is included herewith as Attachment A). The OBD requirements for heavy-duty engines are important, especially considering the increasingly stringent heavy-duty emission standards that will be phased in during the 2007-2010 timeframe. As new engines are being designed to meet these stringent standards (which include the application of new emission control technologies), the OBD system would help ensure that the engines are able to meet these standards and maintain low emissions for the life of the engine. It would accomplish this by monitoring the durability and performance of the emission control components and systems, and by providing technicians with information that would help in diagnosing and fixing the malfunctions. The proposed requirements would allow manufacturers to implement an OBD system on a single engine family for the 2010 through 2012 model years before implementing it on all engines in the 2013 model year.

This phase-in is primarily designed to allow manufacturers to more effectively use their personnel and testing resources (which are already heavily being used to ensure compliance with the 2010 emission standards) and allow them to gain experience on a smaller number of engines prior to widescale implementation.

Among the emission control system and components the proposed OBD regulation would require manufacturers to monitor are the fuel system, catalyst system, exhaust gas recirculation (EGR) system, particulate matter (PM) filter, and cooling system. The proposed heavy-duty OBD regulation would require the calibration of most major emission control system and component monitors to emission levels correlated to the emission standards (i.e., require a fault to be detected before emissions exceed the standards by a certain amount). Additionally, the proposal would require other emission-related components and systems to be monitored for proper performance and functionality. The staff is also proposing that manufacturers be required to conduct post-assembly testing on a sample of production engines and vehicles to ensure that the OBD systems, as built, are able to properly detect malfunctions, store the appropriate fault codes, and illuminate the MIL.

The proposed regulation would also include requirements regarding the availability of diagnostic information to assist repair technicians in effectively diagnosing and repairing vehicles as well as to assist inspectors in the heavy-duty roadside inspection program. The proposed required information would include fault codes, freeze frames, test results, and readiness status. The staff is also proposing to have the on-board computer make available the vehicle identification number (VIN), the software calibration number (CAL ID), and the software calibration verification number (CVN) to simplify roadside inspections and help detect and deter fraud during inspections. Additionally, during OBD II implementation on light-duty vehicles, many communication problems (e.g., the inability to retrieve vehicle data with a scan tool) were found in the field. These problems resulted because the regulation allowed manufacturers to use several different protocols for communication and because manufacturers interpreted the applicable International Standards Organization (ISO) and Society of Automotive Engineers (SAE) protocol standards differently. To help avoid this problem with heavy-duty vehicles, the staff is proposing to allow the use of only two communication protocols for all heavy-duty vehicles. Further, to ensure that vehicles are complying with the applicable ISO and SAE standards in a consistent manner, manufacturers would be required to conduct post-assembly line testing of a sample of production vehicles using a standardized off-board test device developed in conjunction with SAE.

ARB staff is also proposing adoption of a standardized methodology for determining the frequency of OBD monitor operation for most monitors during in-use driving and a minimum operating frequency that manufacturers are required to meet. In the past with OBD II implementation, ARB had found vehicles with OBD II monitors that did not run as frequently as required. In addition, ARB staff had found it difficult to determine whether monitoring frequency was adequate based solely on the written material and data manufacturers provided during certification. To address these problems, ARB staff is proposing the adoption of an in-use monitor performance methodology to help staff determine which OBD monitors would need to be improved or whether the minimum required frequency needs to be modified. To ensure that vehicles are able to meet these new requirements (i.e., calculate and report the monitor frequency value and meet the minimum frequency requirement in accordance with the proposed regulation), the staff is proposing that manufacturers collect data from a sample of in-use vehicles.

In developing this proposal, ARB staff and U.S. EPA staff have been discussing the heavy-duty OBD requirements and U.S. EPA staff has indicated its intent to propose and adopt an OBD regulation for heavy-duty vehicles and engines over 14,000 pounds. U.S. EPA staff have indicated a strong interest in continuing to work with ARB, the heavy-duty industry, and other stakeholders to develop harmonized ARB and federal OBD programs.

Lastly, staff has worked with the engine manufacturers in developing this proposal. As can be expected, however, there are a number of issues where staff and industry differ significantly as to the necessity of or the level of a proposed monitoring requirement. A short summary of the items most likely expected to be discussed at the Board hearing is provided in section XVI "Issues of Controversy" beginning on page 128 of this document.

II. INTRODUCTION AND BACKGROUND INFORMATION

Introduction

OBD systems are comprised mainly of software designed into the vehicle's on-board computer to detect emission-control system malfunctions as they occur. This is done by monitoring virtually every component and system that can cause increases in emissions. With a couple of exceptions, no additional hardware is required to perform the monitoring; rather, the powertrain control computer is designed to better evaluate the electronic component signals that are already available, thereby minimizing any added complexity. When an emission-related malfunction is detected, the OBD system alerts the vehicle operator by illuminating the MIL on the instrument panel. By alerting the operator of malfunctions as they occur, repairs can be sought promptly, which results in fewer emissions over the life of the vehicle. Additionally, the OBD system stores important information, including identifying the faulty component or system and the nature of the fault, which would allow for quick diagnosis and proper repair of the problem by technicians. This helps vehicle owners achieve less expensive repairs and promotes repairs being done correctly the first time.

Currently, California regulations require all 1996 and newer passenger cars, light-duty trucks, and medium-duty vehicles and engines to be equipped with OBD systems (referred to as OBD II systems). ARB first adopted the OBD II regulation (title 13, California Code of Regulations (CCR) section 1968.1) in 1989 and subsequently modified the regulation in regular updates in later years to address, among other things, manufacturers' implementation concerns and, where needed, to strengthen specific monitoring requirements. In 2002, ARB amended the OBD II regulation by adopting title

13, CCR sections 1968.2 and 1968.5, which established OBD II requirements and an OBD II-specific in-use enforcement protocol, respectively, for 2004 and subsequent model year passenger cars, light-duty trucks, and medium-duty vehicles and engines.

The OBD II requirements serve an important role in achieving and maintaining low vehicle emissions. Manufacturers are required to improve their emission control system performance and durability in order to meet the very low and near-zero emission standards of the Low Emission Vehicle II program. Since the OBD II program is designed to ensure maximum emission control system performance for the entire life of the vehicles (regardless of mileage), it is able to monitor the low-emission performance of vehicles and ensure that they are performing as required throughout their useful lives and beyond. This is important, since most emission problems occur as vehicles age and accumulate high mileage.

Input from manufacturers, service technicians, Inspection and Maintenance (I/M) programs, and in-use evaluation programs indicate that the OBD II program is very effective in finding emission problems and facilitating repairs. The United States Environmental Protection Agency (U.S. EPA), in fact, issued a final rule that indicates its confidence in the performance of OBD II systems by requiring states to perform OBD II checks for these newer vehicles and allowing them to be used in lieu of current tailpipe tests in I/M programs. Overall, ARB staff is pleased with the significant and effective efforts of the automotive industry in implementing the program requirements.

In 2004, ARB adopted section 1971, title 13, CCR, requiring implementation of diagnostic systems (i.e., engine manufacturer diagnostic (EMD) systems) on all 2007 and subsequent model year heavy-duty vehicles and engines. These diagnostic system requirements, however, are not as comprehensive as the OBD II requirements, containing no standardization requirements, and requiring monitoring of only a few of the major emission control components and systems, among other things.

Why Require OBD Systems on Heavy-Duty Vehicles and Engines?

Heavy-duty vehicles are an important part of the country’s transportation network. Due to their fuel efficiency, low maintenance costs, and durability, diesel engines are employed on the vast majority of the heavy-duty trucks in lieu of gasoline engines. Unfortunately, the emissions emitted from these heavy-duty trucks, especially diesel trucks, are of great concern. Currently, diesel truck emissions account for about 28 percent and 16 percent of the total statewide mobile source oxides of nitrogen (NOx) and particulate matter (PM) emissions, respectively. NOx is a precursor to ozone as well as a lung irritant, while diesel PM is carcinogenic and has been identified as a toxic air contaminant by ARB. While emissions from heavy-duty diesels are of particular concern, emissions from heavy-duty gasoline vehicles are also of concern, given the state’s ongoing problem in meeting state and federal ambient air quality standards.

The emission standards for heavy-duty vehicles have become increasingly stringent over the years. By 2004, the heavy-duty diesel emission standards for NOx and PM have been reduced by over 60 to 80 percent compared to the standards in 1990. Starting in 2007, both emission standards would be reduced further by 90 percent compared to the 2004 standards. The reduced PM standard starts in 2007 while the reduced NOx standard is phased-in during the 2007 through 2010 timeframe. Emission standards for heavy-duty gasoline vehicles and engines are also reduced in 2008. While the adoption of increasingly stringent standards are a step towards meeting California's air quality goals, there must be some assurance that these standards continue to be met in-use, since emission-related malfunctions can cause vehicle emissions to increase well beyond the standards that they are intended to meet. To meet these stringent standards, manufacturers must improve existing emission control technologies as well as utilize new technologies. The technologies include combinations of electronic powertrain and emission controls as well as exhaust aftertreatment components. Accordingly, in order to maintain low emissions throughout the vehicle's life, the durability and performance of these components and systems must be monitored. Additionally, with these changes comes the development of more complex electronic emission control systems, which increasingly rely on computer-based control. Therefore, the diagnosing of malfunctions related to emission-related components and systems becomes more complicated as well. OBD systems would ensure that emission-related malfunctions are quickly detected as well as properly identified and repaired by providing repair technicians with enough information concerning the malfunctioning component and the type of failure present.

As previously stated, ARB recently adopted diagnostic requirements that apply to heavy-duty vehicles. ARB adopted the EMD regulation to apply to all 2007 and subsequent model year on-road heavy-duty Otto-cycle (gasoline) and diesel engines. However, the requirements in the EMD regulation for heavy-duty vehicles are much less comprehensive than those in the OBD II regulation for light-duty vehicles. Specifically, the EMD regulation contains monitoring requirements for only a few of the major emission control technologies and contains no standardized requirements. That is because the staff developed the regulation to enable engine manufacturers to make minimal or no changes to the existing diagnostic systems on their engines. However, during the EMD rulemaking, staff had indicated its intention to return to the Board in 2005 to adopt more comprehensive diagnostic, testing, and standardization requirements for future heavy-duty engines. Thus, ARB staff is proposing at this time adoption of a separate OBD regulation (proposed title 13, CCR section 1971.1) to apply to all 2010 and subsequent model year heavy-duty gasoline and diesel engines and vehicles.

Staff expects that diesel engine manufacturers will likely be required to substantially revise the emission control systems on all engines during the 2007 to 2010 model year timeframe to meet the 2007 standards. Typically, these modifications will include hardware changes (such as the addition of PM filters) and software modifications (such as EGR flow rates and fuel injection parameters). As such, staff believes that it would be both cost-effective and efficient for manufacturers to use their engineering resources to implement OBD-required modifications at the same time.

What Would the Heavy-Duty OBD Regulation Require?

As stated previously, the proposed heavy-duty OBD regulation would contain more comprehensive diagnostic requirements than the EMD regulation. Specifically, several of the major system and component monitors would be directly calibrated to an emission level correlated to the emission standards (i.e., require a fault to be detected before emissions exceed the standards by a certain amount) while other component monitors (e.g., comprehensive components) would require individual components on the vehicle to be checked for circuit faults and rationality or functionality. For manufacturers concerned about the technical feasibility of meeting the proposed requirements, the staff and industry have identified methods that are expected to be effective in monitoring various emission-related components and systems. In many cases, the staff has identified only one or two potential monitoring strategies for a particular component even though many other equally effective strategies may exist. Further, as history has often shown, manufacturers will be quite innovative and may develop even better techniques as the underlying emission control technology evolves.

The proposed heavy-duty OBD regulation would require the phase-in of OBD systems on heavy-duty gasoline and diesel engines starting with the 2010 model year. For the 2010 through 2012 model years, manufacturers would be required to implement the OBD system on one engine family. All other 2010 through 2012 engine families would be subject to the existing EMD requirements. For 2013, manufacturers would be required to implement OBD on all engine families. This phase-in allows manufacturers to more effectively stagger their resources (especially test cell resources) between meeting the emission standards in 2010 and meeting the OBD requirements for 2010 and 2013. Further, this allows manufacturers to gain valuable experience on a smaller portion of the engine fleet before undertaking widespread implementation.

For some of the major emission control systems and components, the proposed heavy-duty OBD regulation would require malfunctions to be identified before any problem becomes serious enough to cause vehicle emissions to exceed the standards by a certain amount. For diesel engines, these major emission control systems would likely be the fuel system, EGR system, PM filter, and NOx aftertreatment components. For gasoline engines, these major emission control systems would likely be the catalyst, fuel system, oxygen sensor, and, if equipped, EGR system or secondary air system.

The proposed regulation would require manufacturers to correlate component and system performance with emission levels to determine when deterioration of the system or component will cause emissions to exceed a certain emission threshold. For gasoline engines, the proposed regulation would specify this threshold as a multiple of the emission standards (e.g., 1.5 or 1.75 times the standards). For diesel engines, the proposed regulation would specify this threshold as either a multiple of the standards, an additive value above the standards (e.g., 0.2 g/bhp-hr above the standards), or an absolute emission level (e.g., 0.05 g/bhp-hr). When this threshold is exceeded, the proposed regulation would require the diagnostic system to alert the operator to the problem by illuminating the MIL. The malfunction thresholds will be based on the emission standards that the particular engine is certified to, be it an established engine emission standard or a manufacturer-specific family emission limit (FEL) used in accordance with the averaging, banking, and trading program.

Diesel engine manufacturers have expressed concern about developing emission threshold-based monitors, stating that they have had no prior experience developing OBD systems and therefore need some flexibility in the first years of monitor implementation. Therefore, for aftertreatment monitors (e.g., PM filters, catalyst systems), the proposed regulation would allow manufacturers to use a higher emission threshold for fault detection for the 2010 through 2012 model years. For example, the emission threshold for the PM filter performance monitor would be 0.05 g/bhp-hr for the 2010 through 2012 model years which is five times the PM emission standard, and decreases to 0.025 g/bhp-hr for 2013 and subsequent model years. However, staff is proposing more stringent emission thresholds with no phase-in for major components and systems (e.g., EGR and fuel system) located upstream of the aftertreatment as the aftertreatment is expected to compensate for some of the emission increase caused by a deteriorated emission control component, thereby reducing the actual impact on tailpipe emissions. As such, the system should be able to withstand fairly substantial deterioration of these components before the aftertreatment is overwhelmed and tailpipe emissions exceed the proposed thresholds of 1.5 or 1.75 times the standard.

Diesel engines are currently subject to emission standards over three different emission test procedures including the Federal Test Procedure (FTP), the European Stationary Cycle (ESC), and the Not-to-Exceed (NTE) control area. Combined, these cycles cover a substantial portion of the diesel engine operating region to ensure good emission control over the majority of in-use operation. However, for purposes of determining the emission levels for OBD system calibration, manufacturers would only be liable for calibrating to a certain emission threshold on either the FTP or the ESC cycle, whichever is more stringent. This reduces a manufacturer's development workload while still providing reasonable quantification of the emission impact of a malfunction. Further, for the 2010 through 2012 model years, the proposed regulation allows manufacturers to use engineering judgment to determine which of the two test procedures is more stringent and to calibrate accordingly, in lieu of performing actual testing for every component on both cycles.

For the components and systems in which the emission threshold criterion is not sufficient or cannot easily be applied, the proposed regulation would establish different malfunction criteria to identify emission problems. For example, in addition to having to detect engine misfire before emissions exceed 1.5 times the standards on gasoline engines, the proposed regulation would require that misfire levels be detected that will cause catalyst damage due to overheating.

Given that diesel and gasoline applications often utilize different emission control technologies or strategies, the proposed regulation would contain several separate monitoring requirements for diesel and gasoline applications. For example, diesel applications would be required to monitor diesel-related emission control technologies such as particulate filters and NOx absorbers, while gasoline applications would be required to monitor gasoline-related technologies such as evaporative emission systems. Additionally, for emission controls common to both diesel and gasoline engines, the proposed regulation would include a section that details monitoring requirements that apply to both diesel and gasoline applications. These include engine cooling system monitoring and comprehensive component monitoring.

Regarding evaporative system monitoring for gasoline applications, the emission threshold criterion would not be applicable. The proposed regulation would require the OBD system to detect leaks equivalent or greater in magnitude to a 0.090 inch diameter hole. While data from passenger car evaporative system designs show that leaks approaching a 0.020 inch hole begin to rapidly generate excess evaporative emissions (up to 15 times the standard), current monitoring technology for the large tanks typically found on heavy-duty vehicles and serviceability issues limit detection and repair of that size of leak. Further, in the heavy-duty industry, truck builders are currently given significant additional flexibility in fuel tank size, shape, location, and associated hardware. It is impractical for engine manufacturers to develop robust calibrations for very small leaks that would be able to handle the amount of variations that exist in the marketplace today. As a compromise, a larger leak of 0.090" should allow engine manufacturers to place some restrictions on tank size, location, and hardware (more restrictions than exist today), but not to the extent of eliminating virtually all variations, and still robustly detect leaks.

The emission threshold criterion would also not be applicable to monitoring of electronic engine components that can cause emissions to increase when malfunctioning, but generally to less than the malfunction emission thresholds (e.g., 1.5 times the standard). The proposed regulation would require such components (i.e., comprehensive components) to be monitored for proper function on both diesel and gasoline applications. For example, for components that provide input to the on-board computer, the OBD system would be required to monitor for out-of-range values (generally open or short circuit malfunctions) and input values that are not reasonable based on other information available to the computer (e.g., sensor readings that are stuck at a particular value or biased significantly from the correct value). For output components that receive commands from the on-board computer, the OBD system would be required to monitor for proper function in response to these commands (e.g., the system verifies that a valve actually opens and closes when commanded to do so). Monitoring of all such components is important because, while a single malfunction of one of these components may not cause an exceedance of the emission standards, multiple failures could synergistically cause high in-use emissions.[1] Further, the OBD system relies on many of these components to perform monitoring of the more critical emission control devices. Therefore, a malfunction of one of these input or output components, if

[1] The proposed regulation would only require detection of any single component failure that can affect emissions rather than detection of every combination of multiple component degradations that can cause emissions to exceed the standards, due to the overwhelming time and cost resources that would be required to evaluate the latter.

undetected, could lead to incorrect diagnosis of emission malfunctions or even prevent the OBD system from checking for malfunctions.

In addition to malfunction detection requirements, the proposed regulation would require diagnostic repair information to be provided to aid service technicians in isolating and fixing detected malfunctions. For each malfunction detected, a specific fault code would be stored, pinpointing to the extent feasible, the area and nature of the malfunction (e.g., a mass air flow sensor with an inappropriately high reading). The OBD system would also provide technicians with access to current engine operating conditions such as engine speed, engine load, and coolant temperature. The OBD system would even store the operating conditions that exist at the time a malfunction is detected. All of this information would be accessed with the use of a generic scan tool (i.e., a tool that can access all makes and models of vehicles), and would help assist the technician in accurately diagnosing and repairing problems.

Additionally, the proposed regulation would allow exemption from the OBD system requirements for engines that are certified to run on alternate fuels until the 2020 model year. Instead, for 2013 through 2019 model year alternate-fueled engines, the proposed regulation would require manufacturers to implement EMD systems on these engines. They would also be required to monitor for NOx aftertreatment malfunctions. This allowance will reduce the burden on manufacturers of these engines, which are produced in much lower numbers than their gasoline and diesel counterparts and since it is likely that the manufacturers would be required to redevelop a significant portion of the OBD system specifically for alternate-fueled engines (i.e., manufacturers would not be able to use their diesel engine-based OBD systems on alternate-fueled engines because of the vast differences in emission control components). Lastly, the role for alternate fuel engines in the heavy-duty industry is still uncertain and these allowances should provide more time for the market to decide what role these engines will play and in what volumes rather than having manufacturers prematurely elect to discontinue production of these engines partially due to OBD requirements.

What Do the Federal OBD Regulations Require?

Currently, the U.S. EPA only has OBD requirements for light-duty vehicles and trucks and for federally defined "heavy-duty" vehicles and engines with a GVWR between 8,500 to 14,000 pounds. These are the same categories of vehicles covered by ARB's OBD II regulations which apply to light- and medium-duty vehicles (where medium-duty is defined in California as the 8,500 to 14,000 pound GVWR range). Presently, the U.S. EPA does not have OBD requirements for vehicles and engines above 14,000 pounds, which is the weight range for California's “heavy-duty” class. ARB staff and the U.S. EPA staff have been discussing the heavy-duty OBD requirements and the U.S. EPA staff has indicated its intent to propose and adopt an OBD regulation for heavy-duty vehicles and engines over 14,000 pounds. U.S. EPA staff have indicated a strong interest in continuing to work with ARB, the heavy-duty industry, and other stakeholders to develop harmonized ARB and federal OBD programs.

OBD and Heavy-Duty Inspection Programs

As stated before, one of the main purposes of OBD is to keep emissions low for the entire life of the vehicle. In order to achieve this, a mechanism is needed to ensure that emission-related malfunctions detected by the OBD system are repaired in a reasonable timeframe. Before the OBD II system check was incorporated into the I/M program for light- and medium-duty vehicles, California's I/M program (i.e., "Smog Check") relied primarily on tailpipe testing to identify vehicles with emission-related malfunctions. When these vehicles were identified, repair technicians then were required to diagnose the cause of the emission failure and performed the necessary repairs. The effectiveness of the repairs in bringing the vehicle back into compliance can be known with certainty only when the vehicle again undergoes a tailpipe test. The incorporation of OBD II system checks greatly simplifies and improves this process. Instead of measuring tailpipe emissions directly once every two years, the technician will only have to check the OBD II system. If the MIL were not illuminated, nor any fault codes stored, there would be considerable assurance that the vehicle is not emitting excessive emissions (i.e., virtually all the potential sources for an emission problem are operating without defect). In addition, an OBD-I/M check can catch faults of emission-related components and systems that cannot otherwise be checked during a tailpipe-only I/M test, such as cold start emission reduction devices or fuel system malfunctions that occur exclusively outside of the I/M driving conditions.

Currently, ARB has two enforcement programs that target excessive smoke emissions from heavy-duty trucks and buses. The first program, the Heavy-Duty Vehicle Inspection Program (HDVIP), consists of ARB inspectors conducting smoke opacity snap-acceleration tests on diesel-powered vehicles and visual tamper inspections (where inspectors look under the hood for visible signs of tampering) on both diesel and gasoline-powered vehicles at various roadside locations, such as California Highway Patrol weigh stations. The second program, the Periodic Smoke Inspection Program (PSIP), requires owners of heavy-duty truck and bus fleets to perform and maintain records of annual self-inspections of their own vehicles. These also consist of smoke opacity snap-acceleration tests and tamper inspections of the vehicles. These current programs, however, focus mostly on reductions of hydrocarbons and particulate matter (which smoke is mostly composed of) and reflect how the vehicle is performing only at the moment of inspection (as opposed to continuously on the road) and under the conditions tested (i.e., snap acceleration). The incorporation of OBD checks into this program would enable a more thorough inspection by continuously monitoring the entire emission control system while the vehicle is in-use and providing emission-related information at the time of inspection. Further, a heavy-duty vehicle operator will know before the inspection whether the vehicle will pass or fail based on the presence or absence of the MIL warning light. This can eliminate uncertainty on the vehicle operator's part in wondering whether or not the truck will fail the inspection and can lead to reduced risk of citations or notice-of-violations (NOVs).

Enforcement for Heavy-Duty OBD

Under the OBD II requirements for light- and medium-duty vehicles, ARB has adopted a separate, stand-alone enforcement regulation for OBD II systems (title 13, CCR section 1968.5). For heavy-duty OBD, staff anticipates doing the same but does not have a staff proposal at this time. Staff anticipates adopting enforcement regulations specific to heavy-duty OBD compliance under a separate rulemaking (or during a biennial review of this regulation) prior to implementation of OBD systems in the 2010 and subsequent model years. Accordingly, the staff report and proposed regulation do not contain a complete set of specific enforcement provisions.

The proposal does, however, include some items related to enforcement. Specifically, the proposal includes higher interim in-use compliance standards for the OBD monitors that are calibrated to specific emission thresholds. For the 2010 through 2015 model year engines, an OBD monitor would not be considered non-compliant (or subject to enforcement action) unless emissions exceeded twice the OBD threshold without detection of a fault. For example, for a PM filter with an OBD threshold of 0.05 g/bhp-hr PM, a manufacturer would not be subject to enforcement action unless emissions exceed twice that, or 0.10 g/bhp-hr PM, without detection of a malfunction. Additionally, the number of engines that would be liable in-use for compliance with the OBD emission thresholds would be limited. With the proposal, manufacturers would only be liable in-use for the highest sales volume engine rating (e.g., a specific rated power variant) within the one engine family that has OBD in the 2010 through 2012 model years. Other engine ratings in that engine family would have no liability in-use for detecting a fault at the specified emission threshold. For 2013 through 2015 model years, all engine ratings within this original OBD engine family would be liable for meeting the emission thresholds. Additionally, a limited additional number of engine ratings in other engine families would become in-use liable in the 2013 model year. Emission threshold liability for all engines in-use would not take effect until the 2016 model year. These provisions allow manufacturers to gain experience in-use without an excessive level of risk for mistakes and allow them to fine-tune their calibration techniques over a six year period.

Staff has spent some time considering the uniqueness of the heavy-duty industry with separate engine and component suppliers and the difficulties this can present in enforcement. The heavy-duty industry is similar in some aspects to other regulated industries or products such as marine engines, off-road engines, and incomplete vehicles, and ARB has experience in dealing with complicated supplier, manufacturer, importer, and dealer relationships both in certification as well as in enforcement. With OBD being fairly complicated and sensitive to interaction from the various components installed with an engine into an end vehicle, staff expects these relationships may become even further complicated. In the end, however, the vast majority of the proposed OBD requirements would apply directly to the engine or its associated emission controls, and the engine manufacturer would have complete responsibility to ensure those requirements are met. Given the central role the engine and engine control unit would play in the OBD system, the staff anticipates proposing that the party certifying the engine and OBD system (typically, the engine manufacturer) also be the responsible party for in-use compliance and enforcement actions. In this role, the certifying party would be ARB's sole point of contact for noncompliances identified during in-use or enforcement testing. ARB would not take on the role of going beyond identifying the noncompliance to determine the ultimate party responsible for the noncompliance (e.g., engine manufacturer, vehicle manufacturer, other supplier). In cases where remedial action would be required (e.g., recall), the certifying party would take on the responsibility of arranging to bring the vehicles back into compliance. To protect themselves, it is expected that engine manufacturers will require engine purchasers to sign indemnity clauses or other agreements to abide by the build specifications applicable to the engine and to bear ultimate financial responsibility for noncompliances caused by the engine purchaser. Given that heavy-duty engines are already subject to various emission requirements including engine emission standards, labels, and certification, engine manufacturers currently do impose restrictions on engine purchasers to ensure the engines do not deviate from their certified configuration when installed. As such, it is likely the engine manufacturers already require such agreements from engine purchasers to protect themselves. Further, if not done for emission certification purposes, the engine manufacturer likely have similar-type protections in place for items that result in premature engine component failure or warranty cost caused by the engine purchaser (e.g., insufficient engine cooling system installed resulting in overheating and premature engine damage).

III. GENERAL MONITORING REQUIREMENTS

A. Monitoring Conditions

As stated previously, the purpose of the OBD system is to detect malfunctions of the emission control system while the vehicle is being operated. To best achieve this, the OBD monitors would have to be designed to run during conditions routinely encountered by drivers of heavy-duty vehicles. If OBD monitors were designed to run only during extreme (i.e., rarely encountered) conditions, emission-related malfunctions would rarely, if ever, be detected, which could lead to unnecessary excess emissions, defeating the purpose of OBD. While manufacturers may limit the conditions under which certain monitors would run to ensure effective monitoring of the component or system, it is important that these conditions are not so restrictive that monitoring would rarely occur during real-world driving. Given the wide variety of operating patterns used within the heavy-duty industry (e.g., refuse trucks and transit buses to line-haul applications), it is especially imperative that heavy-duty manufacturers design monitors to run under as broad a range of driving conditions as possible.

To ensure this, the staff is proposing some guidelines that manufacturers would need to follow when developing their OBD monitors. The proposed regulation would require that monitors run during conditions that (1) are technically necessary to ensure robust detection of malfunctions, and (2) ensure monitoring will occur during normal vehicle operation. ARB would determine if the monitoring conditions proposed by the manufacturer for each monitor abide by these requirements. The staff is also proposing requirements that would measure the real world monitoring performance of many OBD monitors (see section VII. of the Staff Report for more details). These proposed requirements would assist the staff in determining if the monitoring conditions are sufficiently broad for frequent monitoring during normal operation.

The proposed regulation would require each monitor to run at least once per driving cycle in which the applicable monitoring conditions are met. The proposal would also require certain monitors to run continuously throughout the driving cycle. These include a few major monitors (e.g., fuel system monitor) and most circuit monitors. While a basic definition of a "driving cycle" (e.g., from ignition key on and engine start up to engine shut-off) has been sufficient for passenger cars, the driving habits of many types of vehicles in the heavy-duty industry dictate an alternate definition. Typically, many heavy-duty operators will start the engine and leave it running for an entire day or, in some cases, several days or weeks, continuously. As such, in addition to the basic definition of a driving cycle, the staff is proposing a modification to the definition to also include any period of continuous engine-on operation of four hours to be considered a complete driving cycle and to trigger the start of a new driving cycle. Thus, monitors that are required to run once per driving cycle would be reset to run again (in the same key-on engine start or trip) once the engine has been operated for over four hours continuously. This will avoid an unnecessary delay in detection of malfunctions simply because the heavy-duty vehicle operator has elected to leave the vehicle running continuously for an entire day or days at a time.

B. MIL and Fault Code Requirements

When an emission-related malfunction is detected by the OBD system, there must be some indication to the driver of the presence of this fault so that it can be repaired as soon as possible. In the event of a malfunction, the proposed regulation would require the manufacturer to store a fault code identifying the nature of the malfunction and illuminate the MIL to alert the driver of the presence of the fault.

The staff is proposing to standardize the location and image of the MIL. Generally, the MIL would be required to be located on the driver's side instrument panel and, when illuminated, to display the International Standards Organization (ISO) engine symbol, which is the symbol currently proposed by the National Highway Traffic Safety Administration. The proposed regulation would not allow manufacturers to use the MIL for any other purpose other than those related to OBD (i.e., those purposes specified in the proposed regulation). Manufacturers have expressed their desire to utilize existing engine and transmission-specific lights on the dashboard to indicate both emission-related and non-emission-related malfunctions. While the proposed regulation would not prohibit the additional illumination of the current lights when engine or transmission-related problems occur, the staff believes that a separate, OBD-specific light must also be illuminated in conjunction with the other light when the problem is an emission-related fault. This would significantly help the incorporation of OBD checks into the heavy-duty inspection programs, in which vehicles would "fail" due to the presence of an emission-related fault. If a vehicle did not have an OBD-specific light, heavy-duty vehicle operators, inspectors, and technicians would individually have to determine whether the illumination of an engine or transmission-related light was emission-related or not. Past experience in California with warning lights that combine emission-related and non emission-related faults has shown great discrepancies in interpretation by individual technicians and inspectors and has resulted in unnecessary confusion and difficulty.

Generally, a manufacturer would be allowed sufficient time to be certain that a fault truly exists before illuminating the MIL. It is to the advantage of neither the manufacturer, the vehicle operator, the service technician, nor ARB for the MIL to be illuminated when a repairable malfunction is not truly present. Thus, for most OBD monitoring strategies, manufacturers would be expected to illuminate the MIL only after the same malfunction has occurred on two separate driving cycles. The first time a malfunction is detected, a “pending” fault code identifying the suspected failing component or system would be stored in the on-board computer. If the same malfunction is again detected the next time the vehicle is operated, the MIL would be illuminated and a “confirmed” or “active” fault code would be stored. Alternatively, if the same malfunction was not detected on the second time the vehicle was operated, the pending fault code would be erased. A technician would use the “confirmed” or “active” fault code to determine what system or component has failed, what the exact problem is, and how to fix the problem.

In order to minimize the possibility of the MIL cycling on and off, the staff is proposing specific requirements to prevent the MIL from extinguishing too readily. This should improve technician and vehicle owner confidence in the diagnostic system. Specifically, once the MIL is illuminated, the MIL would not be allowed to extinguish unless the monitor related to the malfunction runs on three subsequent successive driving cycles (or trips) and no longer detects a malfunction present. Thus, in the case of an intermittent fault, the malfunction would need to be present for "two-trips-in-a-row" to illuminate the MIL and subsequently, it would have to not occur for "three-trips-in-a-row" to extinguish the MIL.

The staff is also proposing specific requirements that fault code information be retained for a longer period of time for the purpose of aiding repair technicians. The proposed regulation would allow in most instances a confirmed or previously active fault code to be erased only if the identified malfunction has not been again detected in at least 40 engine warm-up cycles and the MIL is not presently illuminated for that malfunction. This would provide added benefit to the vehicle operator and repair technicians by allowing access to fault information even if the MIL is not currently illuminated.

There may be malfunctions of the MIL itself that would prevent the illumination of the MIL. While a technician or inspector can still determine the status of the MIL (i.e., commanded "on" or "off") by reading electronic information available through a scan tool, if the MIL malfunctions, there would be no indication to the driver of any emission-related faults should they occur. Unidentified malfunctions may cause excess emissions to be emitted from the vehicle and may even cause subsequent deterioration or failure of other components or systems without the driver’s knowledge. In order to prevent this, the proposed regulation would require the manufacturer to provide several means for checking whether the MIL is functioning properly. First, the MIL would be required to illuminate for a minimum of 15 to 20 seconds when the vehicle is in the key-on, engine-off position. This would allow an inspector, technician, or vehicle operator to ensure the MIL is capable of illuminating by simply cycling the key on. While the MIL would be physically illuminated during this functional check, the MIL command status would be required to indicate “off” during this check (unless the MIL was currently being commanded “on” for a detected malfunction).

The manufacturer would also be required to include a second functional check of the MIL. The proposed regulation would require a circuit continuity check of the electrical circuit that is used to illuminate the MIL to verify the circuit is not shorted or open (e.g., burned out bulb). While the MIL will not be able to illuminate when such a malfunction is detected, the electronically readable MIL command status in the on-board computer would be changed from commanded "off" to commanded "on". This precaution would again greatly simplify the heavy-duty inspection program and allows the inspection to be completely automated instead of a combination of pass/fail criteria based on electronic information obtained through a scan tool plus manually inputted visual results entered by the inspector. Feedback from passenger car I/M programs has indicated that the current visual bulb check performed by inspectors is subject to error and has resulted in numerous vehicles being falsely failed or passed. By requiring monitoring of the circuit itself, the entire pass/fail criteria of an inspection program could be determined by the electronic information available through a scan tool, thus better facilitating quick and effective inspections and minimizing the chance for manually-entered errors.

While most monitors are expected to be designed as “two-in-a-row" driving cycle monitors (i.e., illuminate the MIL and store a confirmed fault code in two driving cycles), the proposed regulation would allow manufacturers to seek ARB approval to use “statistical algorithms” in their monitoring strategies, which generally analyze diagnostic information collected over more than two driving cycles. For ARB approval of the alternate statistical MIL illumination and fault code storage protocol, the manufacturer would have to submit information demonstrating that the alternate protocol is able to evaluate the system performance and detect malfunctions in an effective and timely manner equivalent to the standard “two-in-a-row” protocol. The staff is proposing to limit the “run length” of these alternate strategies to six driving cycles on average. With alternate strategies, even with a limit of six on average, some malfunctions would not be detected until 10 or more driving cycles due to the variation associated with the algorithm. Should the limit be increased, the variation would also increase, causing malfunction detections to be delayed until 20 or more driving cycles in some cases, which would not be reasonably timely nor equivalent to the standard MIL illumination protocol.

The proposed regulation would also require manufacturers to illuminate the MIL when the vehicle enters a default mode of operation (e.g., over-temperature management strategies) that can affect emissions or the performance of the OBD system. However, manufacturers would be exempt from illuminating the MIL if either of the following occurs: (1) the strategy causes an overt indication (e.g., illumination of a warning light such as a “hot light”) such that the driver is certain to respond and have the problem corrected, or (2) the default strategy is an auxiliary emission control device (AECD) strategy that is properly activated due to the occurrence of conditions that have been approved by the Executive Officer. The manufacturer would be required to submit documentation supporting the exemption for ARB approval.

Additional detailed technical requirements pertaining to fault codes are provided in section VIII. (Standardization Requirements) of the Staff Report.

IV. PROPOSED MONITORING SYSTEM REQUIREMENTS FOR DIESEL/COMPRESSION-IGNITION ENGINES

A. FUEL SYSTEM MONITORING

Background

An important component in emission control is the fuel system. Proper delivery of fuel (in both quantity and injection timing) plays a crucial role in maintaining low engine-out emissions. The performance of the fuel system is also critical for aftertreatment device control strategies. As such, thorough monitoring of the fuel system is an essential element in an OBD system. The fuel system is primarily comprised of a fuel pump, fuel pressure control device, and fuel injectors. Additionally, the fuel system generally has sophisticated control strategies that utilize one or more feedback sensors to ensure the proper amount of fuel is being delivered to the cylinders. While gasoline engines have undergone relatively minor hardware changes (but substantial fine-tuning in the control strategy and feedback inputs), diesel engines have more recently undergone substantial changes to the fuel system hardware and now incorporate more refined control strategies and feedback inputs.

For diesel engines, a substantial change has occurred in recent years as manufacturers have transitioned to new high-pressure fuel systems. One of the most widely used is a “common-rail” fuel injection system, which is generally comprised of a high-pressure fuel pump, a fuel rail pressure sensor, a common fuel rail that feeds all the individual fuel injectors that directly inject fuel into each cylinder, and a closed-loop feedback system that uses the fuel rail pressure sensor to achieve the commanded fuel rail pressure. Unlike older style fuel systems where fuel pressure was mechanically linked to engine speed (and thus, varied from low to high as engine speed increased), common-rail systems are capable of controlling to any desired fuel pressure independent of engine speed. Increased fuel pressure control allows greater precision relative to fuel quantity and fuel injection timing, and provides engine manufacturers with tremendous flexibility in optimizing the performance and emission characteristics of the engine. The ability of the system to generate high pressure independent of engine speed also improves fuel delivery at low engine speeds.

While most diesel engine manufacturers use common-rail systems, some use improved unit injector systems. In these systems, fuel pressure is generated within the injector itself rather than via an engine-driven high-pressure fuel pump in a common-rail system. Typically, the injector unit is both electrically and hydraulically-controlled. A high-pressure oil pump is used to deliver oil to the injector, which in turn activates a plunger in the injector to increase the fuel pressure to the desired level. Earlier versions of unit injector systems were able to achieve some of the advantages of common-rail systems (e.g., high fuel pressures) but still had limitations on the pressure that they could build based on engine speed. Further, the fuel pressure was a function of engine speed and could not be modified to a lower or higher pressure at a given engine speed. Newer design iterations have created an injector with extra valves that allow the system to deliver higher or lower pressures at a given engine speed. Thus, while there is still some dependence on engine speed for the fuel pressure, it is largely adjustable and can achieve much of the same fuel pressure range a common-rail system is capable of achieving.

Precise control of the fuel injection timing is crucial for optimal engine and emission performance. As injection timing is advanced (i.e., fuel injection occurs earlier), hydrocarbon (HC) emissions and fuel consumption are minimized but oxides of nitrogen (NOx) emissions are increased. As injection timing is retarded (i.e., fuel injection occurs later), NOx emissions can be dramatically reduced but HC emissions, particulate matter (PM) emissions, and fuel consumption increase. Engine manufacturers must continually optimize the system to deliver the desired fuel quantity precisely at the right time.

The common-rail system or improved unit injector system also provides engine manufacturers with the ability to separate a single fuel injection event into discrete events such as pilot (or pre) injection, main injection, and post injection. A system using a pilot injection and a main injection instead of a single injection event has been shown to generate a 16 percent reduction in NOx emissions[2] in addition to providing a substantial reduction in engine noise. Another study has shown that the use of pilot injection versus no pilot injection can lead to a 20 percent reduction in PM emissions and a five percent reduction in fuel usage at a similar NOx level.[3]

Lastly, the high pressures and near infinite control in a common-rail or improved unit injector system begin to open the door for manufacturers to modify the fuel injection pressure during a fuel injection event which results in different fuel quantity injection rate profiles or "shapes." "Rate-shaping," as it is commonly known, allows manufacturers to begin a fuel injection event with a set injection rate and end the injection at a different

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[2] Tullis, S., Greeves G., 1996. "Improving NOx Versus BSFC with EUI 200 Using EGR and Pilot Injection for Heavy-Duty Diesel Engines", SAE 960843 (www.dieselnet.com, Diesel Fuel Injection, Common-Rail Fuel Injection).

[3] Greeves, G., Tullis, S., and Barker, B., 2003, "Advanced Two-Actuator EUI and Emission Reduction for Heavy-Duty Diesel Engines", SAE 2003-01-0698.

injection rate. This could be used to progressively increase the fuel quantity during the injection event and has been shown to lower NOx emissions in laboratory settings.[4]

Given these various aspects of common-rail systems and improved unit injector systems, malfunctions that would affect the fuel pressure control, injection timing, pilot/main/post injection timing or quantity, or ability to accurately perform rate-shaping could lead to substantial increases in emissions (primarily NOx or PM), often times with an associated change in fuel consumption.

Proposed Monitoring Requirements

For diesel engines, the staff is proposing several monitoring requirements to verify the overall fuel system's ability to meet the emission standards and to verify that individual aspects or capabilities of the system are properly functioning.

Fuel System Pressure Control Monitoring

The staff is proposing monitoring requirements that continuously verify the system is able to control to the desired fuel pressure. The OBD system would be required to indicate a malfunction when the system can no longer control the fuel system pressure with the consequence that emissions exceed 1.5 times the applicable standards. If no failure of the system can cause emissions to exceed 1.5 times the applicable standards, then the OBD system would be required to detect a fault when the fuel pressure control system has reached its control authority limits and can no longer increase or decrease the commanded injection quantity to achieve the desired fuel system pressure.

Fuel Injection Quantity Monitoring

The staff is proposing monitoring requirements that verify the fuel system is able to accurately deliver the proper quantity of fuel required for each injection. The OBD system would be required to indicate a fault when the system is unable to accurately deliver the desired fuel quantity with the consequence that emissions exceed 1.5 times the applicable standards. If no failure can cause emissions to exceed 1.5 times the applicable standards, then the OBD system would be required to detect a fault when the fuel injection system has reached its control authority limits and can no longer increase or decrease the commanded injection quantity to achieve the desired fuel injection quantity. Malfunctions or deterioration of the system such as injector deposits or injector wear that restrict flow can result in individual cylinder variations that alter the injection quantity or injection profile and lead to increases in emissions. Unlike gasoline engines, diesel engines have no feedback system that directly verifies the proper fuel quantity. While large decreases in the fuel injection quantity can be noticed by the vehicle operator (e.g., reduction in maximum power output of the engine), small changes go unnoticed and may have a substantial impact on emissions by reducing the ability of the system to accurately deliver fuel (through separate pilot, main, or post injections or timing). As an example, pilot injections typically represent only a few

[4] "Advanced Technologies: Fuel Injection and Combustion," www.dieselnet.com.

percent (e.g., four to five percent) of the total fuel injected for an individual cylinder fueling event but can have a disproportional impact on increases in NOx emissions (e.g., +16 percent). Deterioration or other malfunctions could affect the ability of the system to accurately deliver the pilot injection yet still achieve acceptable performance to the vehicle operator.

Fuel Injection Timing Monitoring

Lastly, the staff is proposing that manufacturers implement monitoring to verify that fuel injection timing is correct; that is, that fuel is injected at the precise time that it is commanded to happen. Small changes in fuel timing (advance or retard) can have significant impacts on emissions. If the injector were to open too soon (due to a deteriorated needle lift return spring, etc.), fuel would be injected too soon and potentially at a lower than desired fuel pressure. If the injector were to be delayed in opening (due to restrictions in the injector body passages, etc.), fuel would be injected later than desired and potentially at a higher fuel pressure than desired. As such, the OBD system would be required to verify that the fuel injection occurs within a manufacturer-specified tolerance of the commanded fuel timing point and indicate a malfunction prior to emissions exceeding 1.5 times any of the applicable standards.

Feedback Control Monitoring

Regarding feedback-controlled fuel systems, staff is proposing that manufacturers indicate a malfunction if the fuel system fails to begin feedback control within a manufacturer specified time interval. Manufacturers would also be required to indicate a malfunction if failure or deterioration of components used as part of the feedback control strategy causes the system to go open loop (i.e., stops feedback control) or default operation of the fuel system. Lastly, manufacturers would also be required to indicate a malfunction if feedback control has used up all of the adjustment allowed by the manufacturer. Malfunctions that cause delays in starting feedback control and malfunctions that cause open loop operation could either be detected with a fuel-system specific monitor or with individual component monitors.

Technical Feasibility of Proposed Monitoring Requirements

For diesel engines, under the light- and medium-duty OBD II requirements, a few passenger cars and several medium-duty applications utilizing diesel engines have been monitoring the fuel system components since the 1997 model year. Recently, this has included vehicles using common-rail fuel injection and improved unit injector systems, the same new technology expected to be used throughout the heavy-duty industry. For some aspects of these high-pressure fuel systems, however, the monitoring proposed by the staff for heavy-duty diesel engines does extend beyond those presently required for existing medium-duty applications.

Fuel System Pressure Control Monitoring

The first monitoring requirement proposed by the staff is to identify malfunctions that prevent the system from controlling the fuel pressure to the desired level. Manufacturers control fuel pressure by using a closed-loop feedback algorithm that allows them to increase or decrease fuel pressure until the fuel pressure sensor indicates they have achieved the desired pressure level. For the common-rail systems currently certified on medium-duty vehicles, the manufacturers are indeed continuously monitoring the fuel system pressure by comparing the actual fuel system pressure sensed by a fuel rail pressure sensor to the target fuel system pressure stored in a software table or calculated by an algorithm inside the on-board computer. A fault is indicated if too large of a difference exists between the two. The error limits are established by engine dynamometer emission tests to ensure a malfunction will be detected before emissions exceed 1.5 times the applicable emission standards. In some cases, manufacturers have developed separate strategies that can identify small errors over a long period of time versus large errors over a short period of time. In other cases, one strategy is capable of detecting both types of malfunctions at the appropriate level. In cases where no fuel pressure error can generate a large enough emission increase to exceed 1.5 times any of the applicable standards, manufacturers are required to set the threshold at their control limits (e.g., when they reach a point where they can no longer increase or decrease fuel pressure to achieve the desired fuel pressure). Several medium-duty applications already meet this monitoring requirement. By its nature, a closed-loop system is inherently capable of being monitored because it simply requires analysis of the same closed-loop feedback parameter that is also being used by the system for control purposes.

Fuel Injection Quantity Monitoring

The second diesel fuel system monitoring requirement being proposed is that the system verify that the proper quantity of fuel is being injected. Again, manufacturers would be required to establish the malfunction criteria by engine dynamometer emission tests to ensure a malfunction will be detected before emissions exceed 1.5 times the applicable emission standards. In cases where no fuel quantity error can generate a large enough emission increase to exceed 1.5 times any of the applicable standards, manufacturers would be required to set the threshold at their control limits (e.g., when they reach a point where they can no longer increase or decrease fuel quantity to achieve the desired fuel quantity).

As there is no overall feedback sensor to indicate that the proper mass of fuel has been injected, this monitoring is more difficult. One manufacturer, however, is currently using a strategy that verifies the injection quantity under very specific engine operating conditions and appears to be capable of determining that the system is accurately delivering the desired fuel quantity. This strategy entails intrusive operation of the fuel injection system during a deceleration event where fuel injection is normally shut off (e.g., coasting or braking from a higher vehicle speed down to a low speed or a stop). During the deceleration, fuel injection to a single cylinder is turned back on to deliver a very small amount of fuel. Typically, the amount of fuel would be smaller than, or perhaps comparable to, the amount of fuel injected during a pilot or pre injection. If the fuel injection system is working correctly, that known injected fuel quantity will generate a known increase in fluctuations (accelerations) of the crankshaft that can be measured by the crankshaft position sensor. If too little fuel is delivered, the measured crankshaft acceleration will be smaller than expected. If too much fuel is delivered, the measured crankshaft acceleration will be larger than expected. This process can even be used to "balance" out each cylinder or correct for system tolerances or deterioration by modifying the commanded injection quantity until it produces the desired crankshaft acceleration and applying a correction or adaptive term to that cylinder to compensate future injections of that cylinder to the desired nominal amount. Each cylinder can, in turn, be cycled through this process and a separate analysis can be made for the performance of the fuel injection system for each cylinder. Even if this procedure requires only one cylinder be tested per revolution (to eliminate any change in engine operation or output that would be noticeable to the driver) and requires each cylinder to be tested on four separate revolutions, this process would only take two seconds for a six cylinder engine decelerating through 1500 rpm.

The crankshaft position sensor is commonly used to identify the precise position of the piston relative to the intake and exhaust valves to allow for very accurate fuel injection timing control and, as such, has sufficient resolution and data sampling within the on-board computer to be able to measure such crankshaft accelerations. Further, in addition to the current use of this strategy by a medium-duty diesel engine manufacturer, a nearly identical crankshaft fluctuation technique has been commonly used on medium-duty diesel engines during idle conditions to determine if individual cylinders are misfiring since the 1997 model year.

Another technique that may be used to achieve the same monitoring capability is some variation on the current cylinder balance tests used by many manufacturers to improve idle quality. In such strategies, fueling to individual cylinders is increased, decreased, or shut off to determine if the cylinder is contributing an equal share to the output of the engine. This strategy again relies on changes in crankshaft/engine speed to measure the individual cylinder's contribution relative to known good values and/or the other cylinders. Such an approach would be viable to effectively determine the fuel injection quantity is correct for each cylinder but has the disadvantage of not necessarily being able to verify the system is able to deliver small amounts of fuel precisely (such as those commanded during a pilot injection).

Staff expects other monitoring techniques will likely surface as manufacturers begin to develop their systems. One other approach that has been newly mentioned but not investigated very thoroughly is the use of a wide-range air-fuel (A/F) sensor in the exhaust to confirm fuel injection quantity. The monitoring concept is that the A/F sensor output can be compared to the measured air going into the engine and calculated fuel quantity injected to see if the two agree. Differences in the comparison may be able to be used to identify incorrect fuel injection quantity.

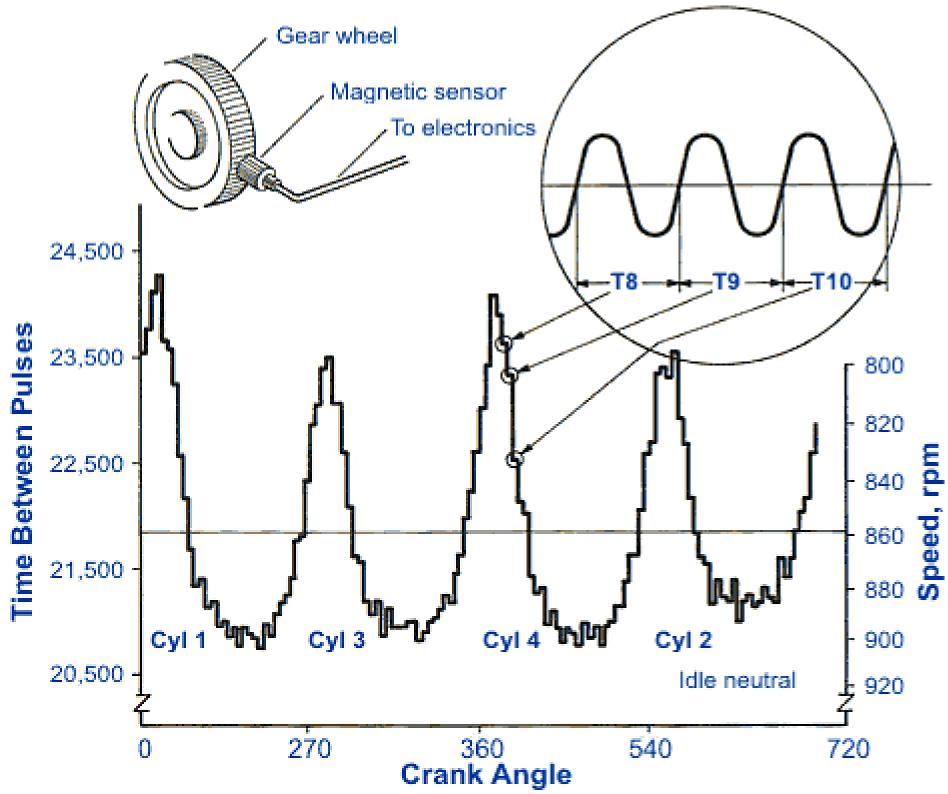
Fuel Injection Timing Monitoring

A similar, or even the same, technique could potentially be used to meet this monitoring requirement. By monitoring the crankshaft speed fluctuation and, most notably, the time at which such fluctuation begins, ends, or reaches a peak, the OBD system could compare the time to the commanded fuel injection timing point and verify the fluctuation occurred within an acceptable time delay from the commanded fuel injection. If the system was working improperly and actual fuel injection was delayed relative to when it was commanded, the corresponding crankshaft speed fluctuation would also be delayed and result in a longer than acceptable time period between commanded fuel injection timing and crankshaft speed fluctuation. Mention of this exact method is found in dieselnet.com[5]:

> In fact, some experiments were conducted at the Bendix Diesel Engine Controls in which a signal was obtained and digitized to analyze the impulsive flywheel motion that results from the torque development. Figure 5 shows the results of this experiment which was conducted on a 4-cylinder Volkswagen diesel engine. While the general observation is that in an engine the flywheel is rotating at a steady speed, it is in fact rotating in a pulsating pattern as shown in Figure 5. By referencing the trace in Figure 5, control engineers at Bendix *were able to infer injection timing and fueling for each cylinder*. Analysis of such trace can yield information regarding when the piston began its downward acceleration. From this determination, an injection timing is inferred by referencing the start of piston acceleration to a set top-dead-center reference. Comparative analysis is then conducted by the electronic control unit *to determine the injection timing for each individual cylinder*. In injection systems where individual cylinder control of the fuel injection is available, adjustments can be made to equalize the effective injection timing in all cylinders. *Likewise, the rate and amount of acceleration of each flywheel impulse can be used to infer the fueling in each cylinder*. Once again, the electronic control unit is capable to adjust the cylinder-to-cylinder fueling rate for smoother engine operation…[Emphasis added]

[5] "Controls for Modern Diesel Engines: Model-Based Control Systems," www.dieselnet.com

Figure 5. Torque Pulses Development in a 4-Cylinder Diesel Engine



Another technique that has been mentioned to staff but not studied in depth is to confirm fuel injection timing involves an electrical feedback signal from the injector to the computer to confirm when the injection occurred. Such techniques would likely use an inductive signature to identify exactly when an injector opened or closed and verify that it was at the expected timing. Staff expects further investigation would be needed to confirm such a monitoring technique would be sufficient to verify fuel injection timing.

Feedback Control Monitoring

The conditions necessary for feedback control (i.e., the feedback enable criteria) are defined as part of the control strategy in the engine computer. The feedback enable criteria are typically based on minimum conditions necessary for reliable and stable feedback control. When the manufacturer is designing and calibrating the OBD system, the manufacture would determine how long it takes to satisfy these feedback enable criteria on a properly functioning engine for the range of in-use operating conditions. The OBD system can evaluate whether it takes too long for these conditions to be satisfied after engine start relative to normal behavior for the system, and a malfunction can be indicated when the time exceeds a specified value (i.e., the malfunction criterion). For example for fuel pressure feedback control, a manufacturer may wait to begin feedback control until fuel system pressure has reached a minimum specified value. For a properly functioning system, pressure builds in the system as the engine is cranked and shortly after starting, and the pressure enable criterion would be reached within a few seconds after engine start. However, a malfunctioning system (e.g., due to a faulty low-pressure fuel pump) may take a significantly longer time to reach the feedback enable pressure. A malfunction would be indicated when the actual time to reach feedback enable pressure exceeds the malfunction criterion.

Malfunctions that cause open-loop or default operation can be readily detected as well. As discussed above, the feedback enable criteria are clearly defined in the computer and are based on what is necessary for reliable control. After feedback control has begun, the OBD system can detect when these criteria are no longer being satisfied and indicate a malfunction. For example, one of the enable criteria could be that the pressure sensor has to be within a certain range. The upper pressure limit would be based on the maximum pressure that can be generated in a properly functioning system. A malfunction would be indicated when the pressure exceeds the upper limit and the fuel system stops feedback control and goes open loop.

The feedback control system has limits on how much adjustment can be made. The limits would likely be based on the ability to maintain acceptable control. Like the feedback enable criteria, the control limits are defined in the computer. The OBD system would continuously track the actual adjustments made by the control system and indicate a malfunction if the limits are reached.

B. MISFIRE MONITORING

Background

Misfire, the lack of combustion in the cylinder, causes increased engine-out hydrocarbon emissions. On gasoline engines, misfire is due to absence of spark, poor fuel metering, and poor compression. Further, misfire can be intermittent on gasoline engines (e.g., the misfire only occurs under certain engine speeds or loads). Consequently, the existing light- and medium-duty OBD II regulation requires continuous monitoring for misfire malfunctions on gasoline engines. However, for diesel engines, manufacturers have maintained that misfire only occurs due to poor compression (e.g., worn valves or piston rings, improper injector or glow plug seating), and when poor compression results in a misfiring cylinder, the cylinder will misfire under all operating conditions. Accordingly, the existing light- and medium-duty OBD II regulation does not require continuous monitoring for misfire malfunctions on diesel engines.

Proposed Monitoring Requirements

For diesel engines, the staff is proposing to require the OBD system to monitor for engine misfire that occurs continuously in one or more cylinders during idle conditions. Additionally, to the extent possible, the OBD system would be required to identify the misfiring cylinder or indicate if multiple cylinder misfiring is occurring (through the storage of the appropriate fault codes). The proposed regulation would require misfire monitoring to occur at least once per drive cycle in which the monitoring conditions (i.e., idle conditions) are met. The proposed regulation would not allow the idle period under which misfire monitoring is to occur to require more than 15 seconds of continuous data collection, nor would it allow more than 1000 continuous engine revolutions of data to make a decision. The proposed regulation would, however, allow manufacturers to conduct this monitoring under conditions other than those conditions stated as long as they meet the general monitoring conditions requirements for all monitors. This would allow for future innovations or alternate strategies that may more robustly detect misfire under non-idle conditions.

This proposed monitoring requirement is identical to the requirement for light- and medium-duty diesel vehicles and is based on the premise that a misfiring diesel engine always misfires, as the engine manufacturers have asserted. However, the staff is concerned that real world malfunctions that cause misfires on diesel engines may occur intermittently or only during off-idle conditions, contrary to manufacturers' assessment. The staff will continue to investigate the possibility of these misfires but currently does not have sufficient information or data to thoroughly validate these concerns. As additional information becomes available for future Board reviews of the HD OBD regulation, the staff may propose a more comprehensive requirement.

Additionally, for 2013 and subsequent model year engines equipped with sensors that can detect combustion or combustion quality (e.g., for use in homogeneous charge compression ignition (HCCI) control systems), the OBD system would required to detect a misfire malfunction prior to emissions exceeding 1.5 times the applicable standards. For these engines, the premise that a misfiring diesel engine misfires under all speeds and loads is clearly not correct. These engines precisely control the combustion process and require additional sensors to accurately measure combustion characteristics. Given the presence of these additional sensors and the likelihood that these types of engines can experience misfire in very specific speed and load regions, continuous monitoring for misfire is appropriate. Staff expects that combustion sensors will only be used on engines that require precise control of air and fuel metering and mixing to achieve proper combustion and maintain low engine-out emission levels.

Technical Feasibility of Proposed Monitoring Requirements

Diesel engines certified under the light- and medium-duty OBD II requirements have been monitoring for misfire since the 1998 model year. The monitoring requirements proposed by staff for heavy-duty diesel engines that do not use combustion sensors are identical to those of current medium-duty diesel applications. The technical feasibility has clearly been demonstrated for these packages. For engines that use combustion sensors, misfire monitoring is feasible because these sensors provide a direct measurement of combustion and, therefore, lack of combustion (i.e., misfire) can be directly measured as well. These sensors are intended to measure various characteristics of a combustion event for feedback control of the precise air and fuel metering. Accordingly, the resolution of sensors that have this capability is well beyond what would be needed to detect a complete lack of combustion.

C. EXHAUST GAS RECIRCULATION (EGR) SYSTEM MONITORING

Background

Since the 1980's, diesel engine NOx emissions have dropped from an uncontrolled level of 15 grams per horsepower-hour (g/hp-hr) to less than four g/hp-hr through the application of advanced technologies. These include turbocharging, charge air cooling, and electronic fuel injection (replacing mechanical systems). In addition, advanced turbocharger systems now provide quick boost response, variable boost pressure, and variable exhaust back pressure to minimize emissions while maximizing fuel economy.

Exhaust gas recirculation (EGR) systems are currently being used to complement these advanced fuel injection and turbocharger systems to meet NOx levels of approximately two g/hp-hr (the 2004 standard is 2.5 g/hp-hr NMHC+NOx with a 0.5 g/hp-hr NMHC cap). Some systems also use an EGR cooler to further reduce NOx emissions. While NOx control technologies have evolved and been refined on gasoline engines over the last 30 years, they had not been as readily adapted to diesel engines. However, as light- and medium-duty diesel engines have been subject to increasingly more stringent emission standards, EGR systems have become more commonplace and will likely be a key emission control component on future heavy-duty diesel engines. In fact, most heavy-duty diesel engines certified for the 2002 model year are equipped with EGR. The staff anticipates that EGR usage will continue as even more stringent heavy-duty diesel standards are phased-in in the near future.

NOx emissions are formed under high combustion chamber temperature and pressure conditions. EGR reduces NOx emissions through two mechanisms. First, recirculated exhaust gas dilutes the intake air (i.e., oxygen and nitrogen are displaced with relatively non-reactive exhaust gases). Dilution of the fresh air provides less reactants to form NOx. Second, EGR absorbs heat from the combustion process, thereby reducing combustion chamber temperatures with an attendant reduction in NOx formation. Heat absorption capacity is in turn a function of EGR flow rate and its temperature, both of which are commonly controlled to minimize NOx emissions. EGR coolers can be added to the EGR system to lower the EGR temperature.

While in theory the EGR system simply routes some exhaust gas back to the intake, production systems can be complex and involve many components to ensure accurate control of EGR flow and maintain acceptable PM and NOx emissions while minimizing effects on fuel economy. To determine the necessary EGR flow rates and control EGR flow, EGR systems normally use the following components: an EGR valve, valve position sensor, boost pressure sensor, intake temperature sensor, intake (fresh) airflow sensor, and tubing or piping to connect the various components of the system. EGR temperature sensors and exhaust backpressure sensors are also commonly used. Additionally, some systems use a variable geometry turbocharger to provide the backpressure necessary to drive the EGR flow. Therefore, EGR is not a stand alone emission control device. Rather, it is carefully integrated with the air handling system (supercharging and intake cooling) to control NOx while not adversely affecting PM emissions and fuel economy.

The staff anticipates manufacturers will need to design EGR systems that accurately and continuously control EGR flow under both transient and steady state load conditions to meet the certification standards applicable for the 2007 and subsequent model years. Further, EGR will have to be accurately controlled under the range of ambient conditions represented by the Not-to-Exceed, or NTE, test to maintain emissions while maximizing in-use fuel economy (refer to section VIII. G. of the Staff Report for more details of the NTE zone). The staff believes all of the components used for control (including auxiliary emission control device or "AECD" operation) purposes can also be used for monitoring. The staff projects that manufacturers would not have to add any components specifically for EGR monitoring.

Proposed Monitoring Requirements

A common phrase in diesel emission control discussions is the "NOx/PM trade-off." Typically, as air-fuel ratio, fuel injection (e.g., start of injection) and EGR parameters are varied, changes that improve NOx emissions tend to increase PM emissions, and changes that improve PM emissions tend to increase NOx emissions. Specifically for EGR system design, excessive EGR flow causes increased PM emissions, and insufficient EGR flow causes increased NOx emissions. When manufacturers design engines and emission control systems, they have to balance this trade-off to achieve both the NOx and PM emission standards.

Given the need to accurately control EGR to maintain acceptable emission levels, the staff is proposing monitoring requirements for flow rate and response rate malfunctions. Additionally, on vehicles equipped with EGR coolers, the OBD system would be required to monitor the cooler for insufficient cooling malfunctions.

EGR Flow Rate Monitoring

Under the staff's proposal, the OBD system would be required to indicate an EGR system malfunction before the change (i.e., decrease or increase) in flow from the manufacturer's specified EGR flow rate causes vehicle emissions to exceed 1.5 times any of the applicable emission standards. In situations where no failure or deterioration of the EGR system that causes a decrease in flow could result in vehicle emissions exceeding 1.5 times any of the applicable standards, the OBD system would be required to indicate a malfunction when the system has reached its control limits such that it cannot increase EGR flow to achieve the commanded flow rate. Similarly, if high flow malfunctions do not cause emissions to exceed 1.5 times any of the applicable standards, the OBD system would be required to indicate a malfunction when the EGR system has reached its control limits such that it cannot reduce EGR flow to achieve the commanded flow rate. Since the EGR system may experience flow rate malfunctions only under some conditions (e.g., a "sticking" EGR valve may not fully open to achieve a desired high flow EGR condition but may still be able to open enough to achieve lower flow rates), the EGR system would be continuously monitored for low and high flow malfunctions.

Under the high flow rate monitor, the OBD system would also be required to monitor for leaking EGR valves. A leaking EGR valve can cause increased PM emissions under conditions where EGR flow is commanded off (i.e., during aggressive engine transients). While a leaking valve may be characterized as a high flow malfunction, it might not necessarily be detected by the high flow diagnostic discussed above. A leaking valve is likely to be caused by a failure of the valve to seat properly when commanded closed, and only has an emission impact under conditions where the valve is commanded closed or turned off. Functional failures for valve opening and valve control would be detected by the flow and response diagnostics discussed above, but these diagnostics may not detect proper valve closing/seating (e.g., if the EGR control system is in an "open loop" mode when it is commanded closed, the flow and response diagnostics would likely be disabled and would not detect the leaking valve).

EGR Response Rate Monitoring

Manufacturers will likely use transient EGR control to meet the emissions standards. EGR rates will be varied with transient engine operating conditions to maintain the balance between NOx and PM emissions. Therefore, staff is proposing a response rate diagnostic to verify that the system has sufficient response. This monitor would detect the inability of the EGR system to modulate EGR flow rates under transient engine conditions. Specifically, the OBD system would be required to indicate a response malfunction of the EGR system if it is unable to achieve the commanded flow rate within a manufacturer-specified time with the consequence that emissions would exceed 1.5 times any of the applicable standards.

The manufacturer would be required to monitor response rate during both increasing and decreasing EGR flow rate conditions. Considering the NOx/PM trade-off discussed above, slow response while trying to increase EGR rates may result in increased NOx emissions. Similarly, slow response while trying to decrease EGR rates may yield in increased PM emissions. Manufacturers would have to account for these trends when determining their malfunction thresholds. Further, it is necessary to monitor response rate under both increasing and decreasing conditions because some malfunctions may only affect response under one (i.e., increasing or decreasing) condition. For example, some EGR valves are held in the closed position with a spring. As the spring deteriorates, it may still properly hold the valve in the closed position, but the valve would close at a slower rate (and might even open at a faster rate). Such a malfunction would only be detected by monitoring the response rate under decreasing EGR conditions.

Feedback Control Monitoring

Regarding feedback-controlled EGR systems, staff is proposing that manufacturers indicate a malfunction if the EGR system fails to begin feedback control within a manufacturer specified time interval. Manufacturers would also be required to indicate a malfunction if failure or deterioration of components used as part of the feedback control strategy causes the system to go open loop (i.e., stops feedback control) or default operation of the EGR system. Lastly, manufacturers would also be required to indicate a malfunction if feedback control has used up all of the adjustment allowed by the manufacturer. Malfunctions that cause delays in starting feedback control and malfunctions that cause open loop operation could either be detected with an EGR - system specific monitor or with individual component monitors.

EGR Cooling System Monitoring

Insufficient EGR cooling can result in higher NOx emissions and can lead to default operation where EGR is shutoff. Accordingly, the staff is proposing monitoring requirements for proper EGR cooling system performance. Specifically, the OBD system would be required to indicate an EGR cooling system malfunction when the reduction in cooling of the exhaust gas causes emissions to exceed 1.5 times any of the applicable standards. For vehicles in which no failure or deterioration of the EGR system cooler could result in a vehicle's emissions exceeding 1.5 times any of the applicable standards, the OBD system would be required to indicate a malfunction when the system has no detectable amount of EGR cooling. Some manufacturers using EGR coolers have indicated that the cooler is not used for emission reduction but rather for EGR valve and system durability. These manufacturers have also requested to forego monitoring of the EGR cooler. If a manufacturer demonstrates that emissions will not be affected under any reasonable driving condition due to a complete lack of EGR cooling, the manufacturer would not be required to monitor the EGR cooler.

At this time, the staff is not proposing monitoring requirements for malfunctions that result in EGR overcooling. While overcooling can lead to accelerated deterioration of the EGR system and engine components due to formation and condensation of corrosive gases, the staff has not reviewed any data indicating emissions are affected due to overcooling of EGR gases. However, to address the condensation issue, manufacturers may employ bypass designs that do not cool the exhaust gas under conditions that can result in condensation. Manufacturers would be required to monitor the bypass system to verify that bypass does not occur when cooling is needed.

Other Monitoring Requirements

Manufacturers would be required to monitor all electronic components of the EGR system (e.g., temperature sensors, valves) for proper function and rationality under the comprehensive component monitoring requirements.

Technical Feasibility of Proposed Monitoring Requirements

EGR Flow Rate Monitoring

The EGR control system has to determine and control the EGR flow. While the system designs from different manufacturers will vary, they will employ a similar closed loop control strategy. First, the control system determines a desired EGR flow rate based on the engine operating conditions. Manufacturers will likely store the desired flow rate/valve position in a lookup table in the engine control module (ECM) (e.g., the desired EGR values, which are based on engine operating conditions such as engine speed and engine load, are established when the manufacturer designs and calibrates the EGR system). The ECM commands the valve to the position necessary to achieve the desired flow. EGR flow rate and/or valve position is feedback-controlled. The ECM calculates or directly measures both fresh air charge and total intake charge. The difference between the total intake charge and fresh airflow is the actual EGR flow. The closed-loop control system continuously adjusts the EGR valve position until the actual EGR flow equals the desired EGR flow.

These closed-loop control strategies could be readily monitored and are the basis for many existing monitors on both gasoline and diesel light- and medium-duty vehicles. The OBD system could evaluate the difference (i.e., error) between the look-up value and the final commanded value to achieve the desired flow rate. When the error exceeds a specific threshold, a malfunction would be indicated. Typically, as the feedback parameter or learned offset increases, there is an attendant increase in emissions, and a correlation could be made between feedback adjustment and emissions. This type of monitoring strategy could be used to detect both high and low flow malfunctions, and is currently in production on a medium-duty vehicle.[6]

While the closed-loop control strategy described above is effective in measuring and controlling EGR flow, some manufacturers are currently investigating the use of a second control loop based on an air-fuel ratio (A/F) sensor (also known as wide-range oxygen sensors or linear oxygen sensors) to further improve EGR control and emissions. With this second control loop the desired air-fuel ratio is calculated based on engine operating conditions (i.e., intake airflow, commanded EGR flow and commanded fuel). The calculated air-fuel ratio is compared to the air-fuel ratio from the A/F sensor and refinements can be made to the EGR and airflow rates (i.e., the control can be "trimmed") to actually achieve the desired rates. On systems that use the second control loop, flow rate malfunctions could also be detected using the feedback information from the A/F sensor and by applying a similar monitoring strategy as discussed above for the primary EGR control loop.

Two types of leaking valves are required to be detected. One type is the failure of the valve to seal when in the closed position (e.g., if the valve or seating surface is eroded, the valve could close and seat, yet still allow some flow across the valve). A flow check is necessary to detect a malfunctioning valve that closes properly but still leaks. EGR flow (total intake charge minus fresh air charge) could be calculated with the valve closed using the monitoring strategy described above for high and low malfunctions, and when flow exceeds unacceptable levels, a malfunction would be indicated. Some

[6] "2003 MY OBD System Operation Summary for 6.0L Diesel Engine" at website http://www.motorcraftservice.com/vdirs/diagnostics/pdf/Dobdsm304.pdf.

cooled EGR systems will incorporate an EGR temperature sensor, which could also be used to detect a leaking EGR valve. For a properly functioning EGR valve, EGR temperature should be a minimum when the EGR valve is closed. An elevated EGR temperature when the valve is closed would indicate a malfunctioning valve. A leaking valve can also be caused by failure of the valve to close/seat (e.g., carbon deposits on the valve or seat that prevent the valve from fully closing). The flow check described above would detect failure of the valve to close/seat but would require a repair technician to further diagnose whether the problem is a sealing or seating problem. Failure of the valve to close/seat could be specifically monitored by checking the zero position of the valve with the position sensor when the valve is closed. If the valve position is out of the acceptable range for a closed valve, a malfunction would be indicated. This type of zero position sensor check is commonly used to verify the closed position of valves/actuators used in gasoline OBD II systems (e.g., gasoline EGR valves, electronic throttle) and would be feasible for diesel EGR valves.

EGR Response Rate Monitoring

The EGR response rate diagnostic is similar to the flow rate diagnostic. While the flow rate diagnostic would evaluate the ability of the EGR system to achieve a commanded flow rate under relatively steady state conditions, the response diagnostic would evaluate the ability of the EGR system to modulate (i.e., increase and decrease) EGR flow as engine operating conditions and, consequently, commanded EGR rates change. Specifically, as engine operating conditions and commanded EGR flow rates change, the monitor would evaluate the time it takes for the EGR control system to achieve the commanded change in EGR flow. This monitor could evaluate EGR response passively during transient engine operating conditions encountered during in-use operation. The monitor could also intrusively evaluate EGR response by commanding a change in EGR flow under a steady state engine operating condition and measuring the time it takes to achieve the new EGR flow rate. Similar passive and intrusive strategies have been developed for variable valve control and/or timing (VVT) monitoring on light- and medium-duty vehicles. Staff believes similar approaches can be used for EGR system monitoring.

Feedback Control Monitoring

Monitoring of EGR feedback control could be performed using the same strategies discussed for fuel system feedback control monitoring in Section IV.A of this report.

EGR Cooling System Monitoring

Some diesel engine manufacturers are currently using exhaust gas temperature sensors as an input to their EGR control systems. On these systems, EGR temperature, which is measured downstream of the EGR cooler, could be used to monitor the effectiveness of the EGR cooler. For a given engine operating condition (e.g., a steady speed/load that generates a known exhaust mass flow and exhaust temperature to the EGR cooler), EGR temperature will increase as the performance of the EGR cooling system decreases. During the OBD calibration process, manufacturers could develop a correlation between increased EGR temperatures and cooling system performance (i.e., increased emissions). The EGR cooling monitor would use such a correlation and indicate a malfunction when the EGR temperature increases to the level that causes emissions to exceed 1.5 times the emission standards.

While the staff anticipates that most, if not all, manufacturers will use EGR temperature sensors to meet future standards, EGR cooler monitoring may also be feasible without an EGR temperature sensor by using the intake manifold temperature (IMT) sensor. EGR cooler performance could be evaluated by looking at the change in IMT (i.e., “delta” IMT) with EGR turned on and EGR turned off (IMT would be higher with EGR turned-on). If there is significant cooling capacity with a normally functioning cooling system, there could be a significant difference in intake manifold temperature with EGR turned on and off. As cooling system performance decreases, the change in IMT would increase. Delta IMT could be correlated to decreased cooling system performance and increased emissions.

D. BOOST PRESSURE CONTROL SYSTEM MONITORING

Background

Turbochargers are used on internal combustion engines to enhance performance by increasing the mass and density of the intake air. Some of the benefits of turbocharging include increased horsepower, improved fuel economy, and decreased exhaust smoke density.[7] Most modern diesel engines take advantage of these benefits and are equipped with turbocharging systems. The power increase associated with turbocharging also brings higher engine stresses, so the robust design of the diesel engine makes the addition of a turbocharger less problematic compared to gasoline engines. While turbochargers increase the efficiency of the diesel engine, exhaust emissions are also improved. Moreover, smaller turbocharged diesel engines can be used in place of larger non-turbocharged engines to achieve the desired engine performance characteristics.

The most widely used turbochargers utilize exhaust gas to spin a turbine at speeds from 10,000 to over 150,000 rpm. The turbine is mounted on the same rotating shaft as an adjacent centrifugal pump. The energy that would otherwise be exhausted as waste heat is used to drive the turbine, which in turn drives the centrifugal pump. This pump draws in fresh air and compresses it to increase the density of the air charge to the cylinders, thereby increasing power.

A boost pressure sensor is typically located in the intake manifold to provide a feedback signal of the current turbo boost. As turbo speed (boost) increases, the pressure in the intake manifold also increases. Hence, engine designers may compare the boost

[7] Ecopoint Inc., 2000. “Turbochargers for Diesel Engines”, DieselNet Technology Guide.

pressure signal to a target boost for the given engine speed and load conditions. Target boost pressure is then obtained by either modulating a wastegate valve or turbo vanes.

Proper boost control is essential to optimize emission levels. Even short periods of over- or under-boost can result in undesired air-fuel ratio excursions and corresponding emission increases. Additionally, the boost control system directly affects exhaust and intake manifold pressures. Another critical emission control system, EGR, is very dependent on these two pressures and generally uses the differential between them to force exhaust gas into the intake manifold. If the boost control system is not operating correctly, the exhaust or intake pressures may not be as expected and EGR may not function as designed. In high-pressure EGR systems, higher exhaust pressures will generate more EGR flow and, conversely, lower pressures will reduce EGR flow. A malfunction that causes excessive exhaust pressures (e.g., wastegate stuck closed at high engine speed) can produce higher EGR flowrates at high load conditions and have a negative impact on emissions.[8]

Manufacturers commonly use charge air coolers to maximize the benefits of turbocharging. As the turbocharger compresses the intake air, the temperature of the intake air charge increases. This increasing air temperature causes the air to expand, which is directionally opposite of what turbocharging is attempting to accomplish. Charge air coolers are used to exchange heat between the compressed air and ambient air (or coolant) and cool the compressed air. Accordingly, a decrease in charge air cooler performance can affect emissions by causing higher intake air temperatures that can lead to increased NOx emissions from higher combustion temperatures.

One drawback of turbocharging is known as turbo lag. Turbo lag occurs when the driver attempts to accelerate quickly from a low engine speed. Since the turbocharger is a mechanical device, a delay exists from the driver demand for more boost until the exhaust flow can physically speed up the turbocharger. In addition to a negative effect on driveability and performance, improper fueling (e.g., over-fueling) during this lag can cause emission increases (typically PM).

To decrease the effects of turbo lag, manufacturers design turbos that spool up quickly at low engine speeds and low exhaust flowrates. However, designing a turbo that will accelerate quickly from a low engine speed but will not result in an over-speed/over-boost condition at higher engine speeds is difficult. That is, as the engine speed and exhaust flowrates near their maximum, the turbo speed increases to levels that cause excessive boost pressures and heat that could lead to engine or turbo damage. To prevent excessive turbine speeds and boost pressures at higher engine speeds, a wastegate is often used to bypass part of the exhaust stream around the turbocharger. The wastegate valve is typically closed at lower engine speeds so that all exhaust is directed through the turbocharger, thus providing quick response from the turbocharger when the driver accelerates quickly from low engine speeds. The wastegate is then opened at higher engine speeds to prevent engine or turbo damage from an over-speed/over-boost condition.

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[8] Ecopoint Inc., 2000. "Effects of EGR on Engine and Emissions", DieselNet Technology Guide.

An alternative to using a wastegate is to use an improved turbocharger design commonly referred to as a variable geometry turbo (VGT). To prevent over-boost conditions and to decrease turbo lag, VGTs are designed such that the geometry of the turbocharger changes with engine speed. While various physical mechanisms are used to achieve the variable geometry, the overall result is essentially the same. At low engine speeds, the exhaust gas into the turbo is restricted in a manner that maximizes the use of the available energy to spin the turbo. This allows the turbo to spool up quickly and provide good acceleration response. At higher engine speeds, the turbo geometry changes such that exhaust gas flow into the turbo is not as restricted. In this configuration, more exhaust can flow through the turbocharger without causing an over-boost condition. The advantage that VGTs offer compared to a waste-gated turbocharger is that all exhaust flow is directed through the turbocharger under all operating conditions. This can be viewed as maximizing the use of the available exhaust energy.

Proposed Monitoring Requirements

The staff is proposing manufacturers be required to monitor boost control systems for proper operation. Manufacturers would be required to continuously monitor for appropriate boost to verify that the turbocharger is operating as designed and conditions of over-boost or under-boost are not occurring. Specifically, the OBD system would be required to indicate a malfunction before an increase or decrease in boost pressure causes emissions to exceed 1.5 times the emission standards.

The staff is also proposing that manufacturers be required to monitor for slow response malfunctions of the VGT system. That is, the OBD system would be required to monitor the time required to reach the desired boost, whether transitioning from high to low boost or low to high, and indicate a malfunction before an increase in the response time causes emission to exceed1.5 times the emission standards.

The proposed regulation would also require the OBD system to monitor the electronic components of the boost control system (e.g., actuators, pressure sensors, position sensors) that provide or receive a signal from the engine control module (ECM) under the comprehensive component requirements for malfunctions such as circuit failures, rationality faults, and functional response to computer commands.

Lastly, the staff is proposing that charge air coolers be monitored for proper cooling of the intake air. That is, the OBD system would be required to detect a charge air cooling system malfunction before a decrease in cooling from the manufacturer's specified cooling rate causes emissions to exceed 1.5 times the emission standards. If no charge air undercooling malfunction can cause emissions to exceed 1.5 times the emission standards, then the cooler would need to be monitored for proper functionality (e.g., verify that some detectable level of cooling is occurring).

Regarding feedback-controlled boost pressure systems, staff is proposing that manufacturers indicate a malfunction if the boost pressure system fails to begin feedback control within a manufacturer specified time interval. Manufacturers would also be required to indicate a malfunction if failure or deterioration of components used as part of the feedback control strategy causes the system to go open loop (i.e., stops feedback control) or default operation of the boost pressure system. Lastly, manufacturers would also be required to indicate a malfunction if feedback control has used up all of the adjustment allowed by the manufacturer. Malfunctions that cause delays in starting feedback control and malfunctions that cause open loop operation could either be detected with a boost pressure system specific monitor or with individual component monitors.

Technical Feasibility of Proposed Monitoring Requirements

To monitor boost control systems, manufacturers are expected to look at the difference between the actual pressure sensor reading (or calculation thereof) and the desired/target boost pressure. If the error between the two is too large or persists for too long, a malfunction would be detected. Manufacturers would need to calibrate the length of time and size of error to ensure robust detection of a fault occurs before the emission malfunction threshold is exceeded. Given the purpose of a closed-loop control system with a feedback sensor is to continually measure the difference between actual and desired boost pressure, the control system is already continually monitoring the difference and attempting to minimize it. As such, a diagnostic requirement to indicate a fault when the difference gets too large and the system can no longer properly achieve the desired boost is essentially an extension of the existing control strategy. Additionally, multiple diesel medium-duty engines are currently certified to the light- and medium-duty OBD II regulation requirements with OBD II systems that meet these proposed requirements.

To monitor for malfunction or deterioration of pressure sensors, manufacturers could validate sensor readings against other sensors present on the vehicle or against ambient conditions. For example, at initial key-on before the engine is running, the boost pressure sensor should read ambient pressure. If the vehicle is equipped with a barometric pressure sensor, the two sensors could be compared and a malfunction indicated when the two readings differ beyond the specific tolerances. A more crude rationality check of the boost pressure sensor may be accomplished by verifying that the pressure reading is within reasonable atmospheric limits for the conditions the vehicle will be subjected to.

Rationality monitoring of VGT position sensors may be accomplished by comparing the measured sensor value to expected values for the given engine speed and load conditions. For example, at high engine speed and loads, the position sensor should indicate that the VGT position is opened more than would be expected at low engine speed and loads. These rationality checks would need to be two-sided. That is, position sensors would be checked for appropriate reading at both high and low engine operating conditions.

Lastly, monitoring of boost pressure feedback control could be performed using the same strategies discussed for fuel system feedback control monitoring in Section IV.A of this report.

E. NON-METHANE HYDROCARBON (NMHC) CONVERTING CATALYST MONITORING

Background

Diesel oxidation catalysts have been used on some off-road diesel engines since the 1960s and on some trucks and buses in the U.S. since the early 1990s. Oxidation catalysts are generally used for reducing HC and carbon monoxide (CO) emissions via an oxidation process. Current diesel oxidation catalysts, however, are also optimized to reduce PM emissions. Specifically, while promoting the chemical oxidation of HC and CO, diesel oxidation catalysts also oxidize the soluble organic fraction (SOF) of diesel particulates. The SOF consists of hydrocarbons adsorbed to the carbonaceous solid particles and may also include hydrocarbons that have condensed into droplets of liquid. At sufficiently high temperatures diesel oxidation catalysts can convert up to 90 percent of HC and CO emissions and 30 percent of PM emissions. Oxidation catalysts may also be used in conjunction with other aftertreatment emission controls such as NOx adsorber systems, selective catalytic reduction (SCR) systems, and PM filters to improve their performance. Manufacturers are likely to include oxidation catalysts to enhance the performance of other aftertreatment emission controls while also using them for a small reduction in HC, CO and PM emissions.

Proposed Monitoring Requirements

The staff is proposing that manufacturers monitor the oxidation catalyst for proper performance. Specifically, the OBD system would be required to indicate a malfunction when the conversion efficiency decreases to a point that emissions exceed 2.0 times the applicable NMHC or PM (or if applicable, NMHC+NOx) standards for 2010-2012 model year engines and 1.5 times the standards for 2013 and subsequent model year engines. If a malfunctioning catalyst cannot cause emissions to exceed the applicable emission threshold, a manufacturer would only be required to functionally monitor the system and indicate a malfunction when no conversion efficiency of the emission of concern could be detected. At a minimum, manufacturers would be required to monitor the catalyst once per driving cycle in which the monitoring conditions are met.

The OBD system would also be required to monitor the oxidation catalyst for other aftertreatment assistance functions. For example, for catalysts used to generate an exotherm to assist PM filter regeneration, the OBD system would be required to indicate a malfunction when the catalyst is unable to generate a sufficient exotherm to achieve regeneration of the PM filter. Similarly for catalysts used to generate a feedgas constituency to assist SCR systems (e.g., to increase NO2 concentration upstream of an SCR system), the OBD system would be required to indicate a malfunction when the catalyst is unable to generate the necessary feedgas constituents for proper SCR system operation. Lastly for catalysts located downstream of a PM filter and used to convert NMHC emissions during PM filter regeneration, the OBD system would be required to indicate a malfunction when the catalyst has no detectable amount of NMHC conversion capability.

In order to determine the proper OBD malfunction threshold for the oxidation catalyst, manufacturers would be required to progressively deteriorate or "age" the catalyst(s) to the point where emissions exceed 2.0 times the standard. The method used to age the catalyst(s) must be representative of real world catalyst deterioration (e.g., thermal and/or poisoning degradation) under normal and malfunctioning operating conditions. For engines with aftertreatment systems that only utilize diesel oxidation catalysts, the catalyst(s) can be aged as a system to the emission threshold for determining the malfunction threshold. However, for engines with aftertreatment systems that utilize multiple catalyst technologies (e.g., an aftertreatment system that includes an oxidation catalyst, catalyzed NOx adsorber, catalyzed PM filter, and lean NOx catalyst), determining the OBD malfunction threshold for the diesel oxidation catalyst becomes more complex since the aging effects on the catalyst are dependent on many factors, including the location of the oxidation catalyst relative to the other aftertreatment technologies and the synergism between each component in the system. Given that each component in the system is dependent on every other component of the overall catalyst system and deteriorate in-use as a system, it would not be appropriate to treat each component in the system independent of the others. Since it is uncertain what exhaust configurations and aftertreatment systems manufacturers will use to comply with the future emission standards for the 2010 and later model years, it is important for the staff to develop and specify a "one-size-fits-all" aging process that accurately represents every possible future aftertreatment configuration. Once diesel aftertreament system designs have stabilized to a level similar to gasoline aftertreatment systems (i.e., the variation of aftertreatment systems is limited) defining a generic catalyst aging plan will be more simple and practical. Until then, the staff would require manufacturers to submit a monitoring plan to the Executive Officer for review and approval of the monitoring strategy, malfunction criteria, and monitoring conditions prior to introduction on a production engine. Executive Officer approval would be based on the representativeness of the catalyst system aging to real world catalyst deterioration under normal and malfunctioning operating conditions, the effectiveness of the monitor to pinpoint the likely area of malfunction, and verification that each catalyst component is functioning as designed.

<u>Technical Feasibility of Proposed Monitoring Requirements</u>

Monitoring of the oxidation catalysts could be performed similar to three-way catalyst monitoring, which uses the concept that oxygen storage correlates well with hydrocarbon and NOx conversion efficiency. Thus, oxygen sensors located upstream and downstream of the catalyst can be used to determine when the oxygen storage capability of the catalyst deteriorates below a predetermined threshold. Determining the oxygen storage capacity would require lean air-fuel (A/F) operation followed by rich A/F operation or vice-versa during catalyst monitoring. Since a diesel engine normally operates lean of stoichiometry, the lean A/F operation portion will be a normal event. However, the rich A/F operation would have to be commanded intrusively when the catalyst monitor is active. The rich A/F operation could be achieved with the engine fuel injectors through late fuel injection or with a dedicated injector in the exhaust upstream of the catalyst. With lean operation, the catalyst will be saturated with stored oxygen. As a result, both the front and rear oxygen sensors should be reading lean. However, when rich A/F operation initiates, the front oxygen sensor would switch immediately to a “rich” indication while the rear oxygen sensor should stay reading “lean” until the stored oxygen in the catalyst is all consumed by the rich fuel mixture in the exhaust. As the catalyst deteriorates, the delay time between the front and rear oxygen sensors reading lean would become progressively smaller. Thus, by comparing the time difference between the responses of the front and rear oxygen sensors to the lean-to-rich or rich-to-lean A/F changes, the performance of the catalyst could be determined. Although conventional oxygen sensors are utilized to illustrate the monitoring method above, these sensors could be substituted with A/F sensors for additional engine control benefits such as EGR trimming and fuel trimming.

Alternatively, if only a functional monitor of the catalyst is required (e.g., a malfunctioning catalyst cannot cause emissions to exceed 2.0 times the emission standard), temperature sensors could be used for monitoring. A functioning oxidation catalyst is expected to provide a significant exotherm when it oxidizes HC and CO. By placing one or more temperature sensors at or near the catalyst, the temperature of the catalyst could be measured. Depending upon the efficiency of the catalyst and the duty cycle of the vehicle, the exotherm may be difficult to discern from the inlet exhaust temperatures. To add robustness to the monitor, the functional diagnostic would need to be conducted during predetermined operating conditions where the amount of HC and CO entering the catalyst are known. This may require an intrusive diagnostic that actively forces the fueling strategy richer (e.g., through late or post injection) than normal for a short period of time. If the measured exotherm does not exceed a predetermined amount that only a properly-working catalyst can achieve, the diagnostic would fail.

For monitoring of the oxidation catalysts capability for other aftertreatment assistance functions (such as generating an exotherm for PM regeneration or proper feedgas for subsequent aftertreatment), a functional monitor is all that is required. It is expected that manufacturers would also use the exotherm approach mentioned above to either directly measure the function (e.g., proper exotherm generation) or correlate to the required function (e.g., proper feedgas generation). For catalysts upstream of the PM filter, it is expected that this monitoring would be conducted during an active regeneration event. For catalysts downstream of the PM filter, however, it is likely that manufacturers will have to intrusively add fuel (either in-exhaust or through in-cylinder post-injection) to create a sufficient exotherm to distinguish malfunctioning catalysts.

F. OXIDES OF NITROGEN (NOx) CONVERTING CATALYST MONITORING

Lean NOx Catalyst

Background

Lean NOx catalysts are essentially reduction catalysts (i.e., catalysts primarily involved in reducing NOx emissions via reduction processes with hydrocarbons) specifically aimed at reducing NOx emissions in the presence of oxygen-rich exhaust gases (i.e., lean conditions) characteristic of diesel engines. Lean NOx catalysts are relatively simple systems that can utilize hydrocarbons from diesel exhaust (a process known as passive lean NOx reduction) to reduce NOx emissions. In general, lean NOx catalysts show increasing NOx conversion rates with increasing HC concentrations. Since the concentration of HC in diesel exhaust is normally low, enrichment of the exhaust with added HC (a process known as active lean NOx reduction) has been pursued as an approach to improve NOx conversion rates. Enrichment of the diesel exhaust can be done by injecting diesel fuel through a dedicated injector into the exhaust system upstream of the catalyst or through late fuel injection into the cylinder. However, even with the addition of HC into the exhaust stream, the average NOx conversion efficiency of lean NOx catalysts remains generally low (less than 30 percent). These catalysts also tend to possess a less favorable efficiency/fuel penalty tradeoff and are most effective in a limited temperature-operating window that does not always correspond to the exhaust temperature at which most NOx emissions are generated. Additionally, catalyst efficiency is affected by HC/NOx ratios and oxygen content in the exhaust.[9] Due to these problems, further improvements need to be made for lean NOx catalysts to achieve widespread commercialization. Currently, lean NOx catalyst technology is primarily aimed at providing small NOx reduction functionality in other technologies, such as diesel oxidation catalysts.

Proposed Monitoring Requirements

The proposed monitoring requirements would require monitoring of the lean NOx catalyst (i.e., catalysts primarily involved in reducing NOx emissions via reduction processes) for proper NOx conversion performance. Specifically, for 2010 through 2012 model year engines with lean NOx catalysts that utilize an active/intrusive diesel injection strategy (i.e., active lean NOx catalysts), the OBD system would indicate a malfunction when the catalyst conversion capability decreases to the point that would cause the engine's NOx emissions to exceed the applicable NOx standards by more than 0.3 g/bhp-hr (e.g., cause emissions to exceed 0.5 g/bhp-hr if the emission standard is 0.2 g/bhp-hr) as measured from an applicable cycle emission test. For 2013 and subsequent model year engines, manufacturers would be required to indicate a malfunction when the conversion efficiency decreases to a point that NOx emissions exceed the applicable NOx standards by more than 0.2 g/bhp-hr. If a malfunctioning catalyst cannot cause emissions to exceed these emission thresholds, a manufacturer would only be required to functionally monitor the system and indicate a malfunction when no NOx conversion efficiency could be detected. At a minimum, manufacturers

[9] "Lean NOx Catalyst," www.dieselnet.com.

would be required to monitor the catalyst once per driving cycle in which the monitoring conditions are met. For active lean NOx catalysts, monitoring must be conducted continuously since precise control of reductant addition throughout the engine's operation range is essential for good NOx performance from the system.

Further, if an active lean NOx catalyst is utilized, the mechanism for adding the fuel reductant must be monitored for proper function. For 2010 through 2012 model year engines, manufacturers would be required to indicate a malfunction of this fault that would cause the engine's NOx emissions to exceed the applicable NOx standards by more than 0.3 g/bhp-hr (e.g., cause emissions to exceed 0.5 g/bhp-hr if the emission standard is 0.2 g/bhp-hr) as measured from an applicable cycle emission test. For 2013 and subsequent model year engines, manufacturers would be required to indicate a malfunction of this fault when NOx emissions exceed the applicable NOx standards by more than 0.2 g/bhp-hr. Additionally, for all 2010 and subsequent model year engines, if the reductant tank is separate from the fuel tank, manufacturers would be required to indicate a malfunction when there is no longer sufficient reductant available (i.e., the reductant tank is empty) or when the incorrect reductant is used.

Technical Feasibility of Proposed Monitoring Requirements

In order to monitor the lean NOx catalyst, manufacturers are projected to use NOx sensors. NOx sensors placed upstream and downstream of the lean NOx catalyst could be used to determine the NOx conversion efficiency directly. Alternatively, manufacturers could potentially use a single NOx sensor placed downstream of the catalyst to measure catalyst-out NOx emissions during engine operation within a controlled window where NOx engine-out (i.e., catalyst inlet) emission performance is relatively stable and can be reliably estimated. Within this engine operation window, NOx catalyst-out measurements could be compared with a calibrated emission threshold for determining a malfunctioning or deteriorated lean NOx catalyst system. If both an upstream and downstream NOx sensor are used for monitoring, the upstream sensor could be used to improve the overall effectiveness of the catalyst by controlling the air-fuel ratio in the exhaust precisely to the levels where the catalyst is most effective.

If an active lean NOx catalyst is utilized, manufacturers would be required to monitor the mechanism for adding the fuel reductant for proper function. This could be done by using a temperature sensor located near or at the catalyst to determine if an exotherm resulting from the injection has occurred. A temperature sensor placed near or at the catalyst is projected to be needed for control purposes on these catalysts to determine when the catalyst is active. As previously described, lean NOx catalysts tend to have a narrow temperature range where they are most effective. Adding reductant when the catalyst is not sufficiently active would adversely affect fuel economy without a reduction in emission levels. Therefore, a temperature sensor placed in the exhaust could help determine when reductant injection should occur. This same sensor can also be used to monitor the injection. Alternatively, the NOx sensors that are used to monitor the lean NOx catalyst can be utilized to determine if the injection has occurred. Since NOx sensors also have the capability to determine the air-fuel ratio in the exhaust stream, the diesel fuel injection into the exhaust can also be verified with this sensor.

Selective Catalytic Reduction (SCR) Catalyst

Background

The SCR catalyst has been used on power plants and stationary engines since the 1970s and is now being developed for use on on-road diesel engines. SCR catalysts are considered one of the most promising exhaust aftertreatment technologies for NOx control. While lean NOx catalysts use hydrocarbons as reductants to reduce NOx, SCR systems use nitrogen-containing compounds such as ammonia or urea, which are injected from a separate reservoir into the gas stream before the catalyst. Currently the SCR system, with NOx reduction rates of over 80 percent achieved on heavy-duty engines, is one of the more promising catalyst technologies capable of achieving the most stringent future low NOx emission standards.

SCR catalyst systems require an accurate ammonia control system to inject precise amounts of reductant. Currently, urea is considered the best reductant for providing ammonia on heavy-duty applications due to its non-toxicity, ease of transport and handling, and potentially wide availability. At temperatures above 160 degrees Celsius, urea thermally decomposes to ammonia in the exhaust, thereby providing ammonia to the SCR catalyst. Concerning ammonia, an injection rate that is too low may result in lower NOx conversions while an injection that is too high may release unwanted ammonia emissions (referred to as ammonia slip) to the atmosphere. In general, ammonia to NOx ratios of around 1:1 are used to provide the highest NOx conversion rates with minimal ammonia slip. Therefore, it is important to inject just the right amount of ammonia appropriate for the amount of NOx in the exhaust. For stationary source engines, estimating the exhaust NOx levels is fairly easy since the engine usually operates at a constant speed and load and the NOx emission rate is generally stable. However, on-road diesel engines operate over a range of speeds and loads, thereby making NOx exhaust estimates difficult without a dedicated NOx sensor in the exhaust. With an accurate fast response NOx sensor, closed-loop control of the ammonia injection can be used to achieve and maintain the desired ammonia/NOx ratios in the SCR catalyst for high NOx conversion efficiency (i.e., greater than 90 percent) necessary to achieve the 2010 emission levels under various engine operating conditions. Currently, however, such an accurate fast response NOx sensor is not yet available. It has been estimated that achieving the 2010 NOx emission standards with SCR systems will require NOx sensors that can measure NOx levels accurately around the 10 to 20 ppm range with little cross sensitivity to ammonia.[10] Current NOx sensors do not yet meet these specifications, but sensor technology is improving quickly such that zero to 500 ppm resolution sensors have been achieved[11] and zero to 100 ppm

[10] Song, Q. and Zhu, G., "Model-based Closed-loop Control of Urea SCR Exhaust Aftertreatment System for Diesel Engine," SAE Paper 2002-01-0287.

[11] Kato, N., Kokune, N., Lemire, B., and Walde, T., "Long Term Stable NOx Sensor with Integrated In-Connector Control Electronics," SAE Paper 1999-01-0202.

sensors are being developed.[12] With further development, sensors are expected to achieve the required NOx sensitivity in time for the 2010 emission standards. Regarding cross-sensitivity to ammonia, work has been done that indicates ammonia and NOx measurements can be independently measured by conditioning the output signal.[13] This signal conditioning method resulted in a linear output for both ammonia and NOx from the NOx sensor downstream of the catalyst.

For SCR systems, closed-loop control of the reductant injection could be achieved using one or two NOx sensors. If two are used, the first NOx sensor would be located upstream of the catalyst and the reductant injection point and would be used for measuring the engine-out NOx emissions and determining the amount of reductant injection needed to reduce emissions. The second NOx sensor located downstream of the catalyst would be used for measuring the amount of ammonia and NOx emissions exiting the catalyst and providing feedback to the reductant injection control system. If the downstream NOx sensor detects too much NOx emissions exiting the catalyst, the control system can inject higher quantities of reductant. Conversely, if the downstream NOx sensor detects too much ammonia slip exiting the catalyst, the control system can decrease the amount of reductant injection. With further development, staff projects that manufacturers will be able to model the upstream NOx levels (based on other engine operating parameters such as engine speed, fuel injection quantity and timing, EGR flow rate), thereby eliminating the need for the front NOx sensor for both control and monitoring purposes.

In addition to exhaust NOx levels, another important parameter for achieving high NOx conversion rates with minimum ammonia slip is catalyst temperature. SCR catalysts have a defined temperature range where they are most effective. For example, platinum catalysts are effective between 175 and 250 degrees Celsius, vanadium catalysts are effective between 300 and 450 degrees Celsius, and zeolite catalysts are most effective between 350 and 600 degrees Celsius. Injecting urea into the SCR catalyst outside the effective temperature band could lead to deactivation through poisoning or collapse of the crystal structure of the catalyst.[14] Furthermore, the reaction kinetics between ammonia and NOx are sensitive to temperature. In general, at higher catalyst temperatures, more ammonia needs to be added to the exhaust to achieve the desired NOx conversion rates while at lower temperatures, ammonia injection rates need to be limited to prevent ammonia slip.[15] To determine exhaust catalyst temperature for reductant control purposes, manufacturers are likely to use temperature sensors placed in the exhaust system. It is projected that only one temperature sensor positioned just upstream of the SCR system will be utilized for reductant injection control purposes.

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[12] Kobayashi, N., et al., “Development of Simultaneous NOx/NH3 Sensor in Exhaust Gas,” Mitsubishi Heavy Industries, Ltd., Technical Review Vol.38 No.3 (Oct. 2001).

[13] Schaer, C. M., Onder, C. H., Geering, H. P., and Elsener, M., “Control of a Urea SCR Catalytic Converter System for a Mobile Heavy Duty Diesel Engine,” SAE Paper 2003-01-0776.

[14] “Selective Catalyst Reduction,” www.dieselnet.com.

[15] Van Helden, R., van Genderen, M., van Aken, M., et al., “Engine Dynamometer and Vehicle Performance of a Urea SCR-System for Heavy-Duty Truck Engines,” SAE Paper 2002-01-0286.

Production SCR catalyst systems may also contain auxiliary catalysts to improve the overall NOx conversion rate of the system. An oxidation catalyst is often positioned downstream of the SCR catalyst to help control ammonia slip on systems without closed-loop control of ammonia injection. The use of a "guard" catalyst could allow higher ammonia injection levels, thereby increasing the NOx conversion efficiency without releasing un-reacted ammonia into the exhaust. The guard catalyst can also reduce HC and CO emission levels and diesel odors. However, increased N_2O emissions may occur and NOx emission levels may actually increase if too much ammonia is oxidized in the catalyst. Some SCR systems may also include an oxidation catalyst upstream of the SCR catalyst and urea injection point to generate NO_2 for reducing the operating temperature range and/or volume of the SCR catalyst. Studies have indicated that increasing the NO_2 content in the exhaust stream can reduce the SCR temperature requirements by about 100 degrees Celsius.[16] This "pre-oxidation" catalyst also has the added benefit of reducing HC emissions. However, additional sulfate PM emissions can occur when high sulfur fuel is used.[15]

Despite its high NOx conversion efficiency, there are several concerns in applying SCR systems to mobile applications. First, proper injection control is difficult under transient conditions. Second, design modifications to accommodate the necessarily large SCR catalysts may be difficult and costly. Further, there are many as yet unresolved issues regarding infrastructure changes that would be necessary to address the storage and refilling of the reductant supply on vehicles. Nonetheless, there is extensive research going on in the development and improvement of applying SCR to heavy-duty vehicles.

Proposed Monitoring Requirements

The proposed regulation would require monitoring of SCR catalyst systems for proper NOx conversion performance. Specifically, for 2010 through 2012 model year engines, manufacturers would be required to indicate a catalyst malfunction when the catalyst conversion capability decreases to the point that would cause an engine's NOx emissions to exceed any of the applicable NOx standards by more than 0.3 g/bhp-hr (e.g., cause emissions to exceed 0.5 g/bhp-hr if the emission standard is 0.2 g/bhp-hr) as measured from an applicable cycle emission test. For 2013 and subsequent model year engines, manufacturers would be required to indicate a catalyst malfunction when the catalyst conversion capability decreases to the point that would cause an engine's NOx emissions to exceed any of the applicable NOx standards by more than 0.2 g/bhp-hr. If no failure or deterioration of the catalyst NOx conversion capability could result in an engine's NOx emissions exceeding any of the applicable standards by more than thresholds specified above, a manufacturer would only be required to functionally monitor the system and indicate a malfunction when no conversion efficiency of the emission(s) of concern could be detected.

[16] Walker, A. P., Chandler, G. R., Cooper, B. J., et al., "An Integrated SCR and Continuously Regenerating Trap System to Meet Future NOx and PM Legislation," SAE Paper 2000-01-0188.

The proposed regulation would also require monitoring of the performance of the reductant injection system. The proposed malfunction criteria for the reductant injection system are the same as the criteria for the catalyst system conversion efficiency. Specifically for 2010 through 2012 model year engines, manufacturers would be required to indicate a reductant injection system malfunction when the performance of the reductant injection system decreases to the point that would cause an engine's NOx emissions to exceed any of the applicable NOx standards by more than 0.3 g/bhp-hr (e.g., cause emissions to exceed 0.5 g/bhp-hr if the emission standard is 0.2 g/bhp-hr) as measured from an applicable cycle emission test. For 2013 and subsequent model year engines, manufacturers would be required to indicate a catalyst malfunction when the catalyst conversion capability decreases to the point that would cause an engine's NOx emissions to exceed any of the applicable NOx standards by more than 0.2 g/bhp-hr. If a reductant injection system malfunction cannot cause emissions to exceed these emission levels, manufacturers would be required to indicate a reductant injection system malfunction when the system has reached its control limits and can no longer deliver the desired quantity of reductant. Additionally, for all 2010 and subsequent model year engines, if the reductant tank is separate from the fuel tank, manufacturers would be required to indicate a malfunction when there is no longer sufficient reductant available (i.e., the reductant tank is empty) or when the incorrect reductant is used. Since precise control of reductant addition is essential for good NOx performance from the SCR system, manufacturers would be required to continuously monitor the reductant injection system while it is in operation.

Technical Feasibility of Proposed Monitoring Requirements

As mentioned earlier, current NOx sensor technology tends to have a cross-sensitivity to ammonia (i.e., as much as 65 percent of ammonia can be read as NOx).[13] Although this cross-sensitivity can be detrimental to SCR controls (i.e., reductant injection/NOx reduction efficiencies), it is actually beneficial for monitoring purposes. Monitoring of the catalyst can be done by using the same NOx sensors that are used for SCR control. When the SCR catalyst is functioning properly, the upstream sensor should read high (for high NOx levels) while the downstream sensor should read low (for low NOx and low ammonia levels). With a deteriorated SCR catalyst, the downstream sensor should read similar values as the upstream sensor or higher (i.e., high NOx and high ammonia levels) since the NOx reduction capability of the catalyst has diminished. Therefore, a malfunctioning SCR catalyst could be detected when the downstream sensor output is near or greater than the upstream sensor output. A similar monitoring approach can be used if a manufacturer models upstream NOx emissions instead of using an upstream NOx sensor. In this case, the comparison is simply made between the modeled upstream NOx value and the downstream sensor value.

Monitoring of the fuel reductant injection functionality could be done in a manner similar to that for lean NOx catalyst monitoring. The same temperature sensor that is used for control purposes could also be used for monitoring the injection. With proper injection, the catalyst should see a temperature increase afterwards. In addition, the NOx sensors that are used for control purposes could be used to monitor the reductant injection. With a properly functioning injector, the downstream NOx sensor should see a change from high NOx levels to low NOx levels. In contrast, a lack of reductant injection would result in continuously high NOx levels at the downstream NOx sensor. Therefore, a malfunctioning injector could be found when the downstream NOx sensor continues to measure high NOx after an injection event has been commanded.

Reductant level monitoring can be conducted by utilizing the existing NOx sensors that are used for control purposes. Specifically, the downstream NOx sensor can be used to determine if the reductant tank no longer has sufficient reductant available. Similar to the fuel reductant injection functionality monitor described previously, when the reductant tank has sufficient reductant quantities and the injection system is working properly, the downstream NOx sensor should see a change from high NOx levels to low NOx levels. If the NOx levels remain constant both before and after reductant injection, then the reductant was not properly delivered and either the injection system is malfunctioning or there is no longer sufficient reductant available for injection in the reservoir. Alternatively, reductant level monitoring can also be conducted by utilizing a dedicated “float” type level sensor similar to the ones used on fuel tanks to determine sufficient reductant levels. Some manufacturers may prefer using a dedicated reductant level sensor in the reductant tank to inform the vehicle operator of current reductant levels with a gauge on the instrument panel. If such a sensor is utilized by the manufacturer for operator convenience, it can also be used to monitor the reductant level in the tank. The level sensor will provide an output (e.g., voltage) that is dependent upon the reductant level. When the output of the level sensor decreases below a calibrated voltage for an empty tank, there is no longer sufficient reductant available for proper function of the SCR system.

Monitoring for incorrect reductant can also be conducted indirectly by utilizing the existing NOx sensors that are used for control purposes. If an improper reductant is utilized, the SCR system will not function properly. Therefore, NOx emissions downstream from the SCR catalyst will remain high both before and after injection. The downstream NOx sensor will see the high NOx levels after injection and inform the OBD system of a problem.

G. NOx ADSORBER MONITORING

Background

NOx adsorbers are another NOx control technology that has been experiencing significant progress in development and optimization. This is one of the newer technologies being optimized for use in diesel vehicles as well as lean-burn gasoline vehicles. NOx adsorber systems generally consist of a conventional three-way catalyst (e.g., platinum) with NOx storage components (i.e., adsorbents) incorporated into the washcoat. The concept of the NOx adsorber involves the trapping, release, and reduction of NOx from the exhaust stream in the catalyst washcoat. The adsorbers chemically bind (i.e., “trap”) the oxides of nitrogen during lean engine operation. Generally, when the storage capacity of the adsorbers is saturated, regeneration occurs and the stored NOx is released and converted. This occurs under rich engine operation and includes the chemical reduction of the released NOx to nitrogen by carbon monoxide, hydrogen, and hydrocarbons on a precious metal site. The rich running conditions, which generally last for several seconds, are typically achieved using a combination of intake air throttling (to reduce the amount of intake air), exhaust gas recirculation, and post-combustion fuel injection.

NOx adsorber systems have demonstrated NOx reduction efficiencies from 50 percent to in excess of 80 to 90 percent. This efficiency has been found to be highly dependent on the fuel sulfur content because NOx adsorbers are extremely sensitive to sulfur. The NOx adsorption material has a greater affinity for sulfur compounds than NOx. Thus, sulfur compounds can saturate the adsorber and limit the number of active sites for NOx adsorption, thereby lowering the NOx reduction efficiency. Accordingly, low sulfur fuel is required to achieve the greatest NOx reduction efficiencies. Although new adsorber washcoat materials are being developed with a higher resistance to sulfur poisoning and ultra-low sulfur fuel will be required in the future, it is projected that NOx adsorber systems will still be subject to sulfur poisoning and will require a sulfur regeneration mechanism.[17] Sulfur poisoning, however, is generally reversible through a desulfurization process, which requires high temperatures (i.e., 500 to 700 degrees Celsius) accompanied by a rich fuel mixture that can be achieved with post-injection and installation of a light-off catalyst upstream of the NOx adsorber. Because the sulfur regeneration process takes much longer (e.g., several minutes) and requires more fuel and heat than the NOx regeneration step, permanent thermal degradation of the NOx adsorber and fuel economy penalties may result from too frequent sulfur regeneration. However, if regeneration is not done frequently enough, NOx conversion efficiency is compromised and fuel economy penalties will also be incurred from excessive purging of the NOx adsorber.[18]

Installation of sulfur traps upstream of the NOx adsorber can help in alleviating sulfur poisoning problems. The sulfur trap is essentially an adsorber catalyst aimed at trapping sulfur compounds. Similar to the NOx adsorber, once the sulfur trap becomes saturated, the trap must undergo sulfur regeneration. Unfortunately, depending on the temperatures, this regenerated sulfur may be re-adsorbed downstream in the NOx adsorber, so strategies must be carefully developed to minimize this effect (e.g., allowing sulfur trap regeneration to occur less frequently than NOx adsorber regeneration or using bypass valves).

In order to achieve and maintain high NOx conversion efficiencies while limiting negative impacts on fuel economy and driveability, vehicles with NOx adsorption systems will require precise air-fuel control in the engine and in the exhaust stream. Many of these control strategies are still undergoing rapid development. However, diesel manufacturers are expected to utilize NOx sensors and temperature sensors to

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[17] Bailey, O., H., Dou, D., and Molinier, M., "Sulfur Traps for NOx Adsorbers: Materials Development and Maintenance Strategies for Their Application," SAE Paper 2000-01-1205; "NOx Adsorbers," www.dieselnet.com.

[18] Ingram, G. A. and Surnilla, G., "On-Line Estimation of Sulfation Levels in a Lean NOx Trap," SAE Paper 2002-01-0731.

provide the most precise closed-loop control for the NOx adsorber system.[19] These sensors will provide the adsorber control system with valuable information regarding the NOx levels, oxygen levels/air-fuel ratio, and adsorber temperatures that are needed to achieve and maintain the highest NOx conversion efficiencies possible with minimum fuel consumption penalties during all types of operating conditions. Further, these same sensors can also be used to monitor the adsorber system as will be described later.

Alternatively, if NOx sensors are not used to control the NOx adsorber system, it is projected that A/F sensors (located upstream and downstream of the adsorber) can be used effectively as a substitute. A/F sensors are currently used by one manufacturer on a gasoline-fueled vehicle equipped with a NOx adsorber system to control and monitor the system, and at least one other gasoline-fueled engine manufacturer plans to introduce a similar system soon. Although manufacturers have previously expressed concerns regarding the durability of A/F sensors in diesel applications, these concerns apparently have been sufficiently addressed since at least one diesel manufacturer is using A/F sensors for EGR control. On diesel applications, A/F sensors have several advantages over NOx sensors including lower cost, wide availability, and a mature technology. However, A/F sensors cannot provide an instantaneous indication of tailpipe NOx levels, which would allow the control system to precisely determine when the adsorber system is filled to capacity and regeneration should be initiated. If A/F sensors are used in lieu of NOx sensors, an estimation of NOx engine-out emissions and their subsequent storage in the NOx adsorber can be achieved indirectly through modeling. However, this may require significant development work.

Proposed Monitoring Requirements

To ensure the desired NOx emission levels are achieved throughout the engine's useful life, the NOx adsorber must maintain a high conversion efficiency. Therefore, the staff is proposing that manufacturers monitor the NOx adsorber for proper performance. The OBD system would be required to indicate a malfunction when the adsorber capability decreases to a point such that emissions exceed a certain NOx emission threshold. For 2010 through 2012 model year engines, the threshold is 0.3 g/bhp-hr above the NOx emission standard, and for 2013 and subsequent model year engines, the threshold is 0.2 g/bhp-hr above the NOx emission standard. If a malfunctioning NOx adsorber cannot cause emissions to exceed the malfunction emission threshold, a manufacturer would only be required to functionally monitor the system and indicate a malfunction when no NOx adsorber capability could be detected.

Additionally, due to the importance of desulfurization on the performance of the NOx adsorber, the NOx adsorber system diagnostic must be sufficiently robust to distinguish poor NOx conversion performance from temporary/reversible sulfur poisoning. Although manufacturers would not be required to separately monitor for proper desulfurization, manufacturers would be required to design their NOx adsorber diagnostic to be able to rule out temporary sulfur poisoning as the source of poor NOx conversion performance. If the NOx adsorber diagnostic continues to indicate poor

[19] "NOx Adsorbers," www.dieselnet.com.

performance after temporary sulfur poisoning has been ruled out (e.g., immediately after desulfurization), the adsorber system would be considered malfunctioning and the MIL would be illuminated.

Additionally, for NOx adsorber systems that use active or intrusive injection (e.g., in-cylinder post-fuel injection) to achieve desorption of the adsorber, the OBD system would be required to indicate any malfunction of the injection system that would prevent desorption of the NOx adsorber.

Regarding feedback-controlled injection systems, staff is proposing that manufacturers indicate a malfunction if the injection system fails to begin feedback control within a manufacturer specified time interval. Manufacturers would also be required to indicate a malfunction if failure or deterioration of components used as part of the feedback control strategy causes the system to go open loop (i.e., stops feedback control) or default operation of the injection system. Lastly, manufacturers would also be required to indicate a malfunction if feedback control has used up all of the adjustment allowed by the manufacturer. Malfunctions that cause delays in starting feedback control and malfunctions that cause open loop operation could either be detected with an injection - system specific monitor or with individual component monitors.

Technical Feasibility of Proposed Monitoring Requirements

As mentioned earlier, either NOx sensors or A/F sensors along with a temperature sensor are projected to be used for controlling the NOx adsorber system. These same sensors could also be used to monitor the adsorber system. The use of NOx sensors placed upstream and downstream of the adsorber system would allow the system's NOx reduction performance to be continuously monitored. For example, the upstream NOx sensor on a properly functioning adsorber system operating with lean fuel mixtures, will read high NOx levels while the downstream NOx sensor should read low NOx levels. With a deteriorated NOx adsorber system, the upstream NOx levels will continue to be high while the downstream NOx levels will also be high. Therefore, a malfunction of the system can be detected by comparing the NOx levels measured by the downstream NOx sensor versus the upstream sensor. With further development, staff projects that manufacturers will be able to model the upstream NOx levels (based on other engine operating parameters such as engine speed, fuel injection quantity and timing, EGR flow rate), thereby eliminating the need for the front NOx sensor for both control and monitoring purposes.

Alternatively, if NOx sensors are not used by the adsorber system for control purposes, monitoring of the system could be conducted by using A/F sensors to replace one or both of the NOx sensors.[18] Under lean engine operation conditions with a properly operating NOx adsorber system, both the upstream and downstream A/F sensors will indicate lean mixtures. However, when the exhaust gas is intrusively commanded rich, the upstream A/F sensor will quickly indicate a rich mixture while the downstream O2 sensor should continue to see a lean mixture in the exhaust due to the release and reduction of NO_2 in the adsorber. Once all of the stored NO_2 has been reduced, the downstream A/F sensor will indicate a rich reading. The more NOx that is stored in the adsorber, the longer the delay before the downstream A/F sensor indicates a rich exhaust gas. Thus, the time differential between the upstream and downstream A/F sensors' lean-to-rich indication is a gauge of the NOx adsorption capability of the adsorber and can be calibrated to indicate different levels of performance. Fresh NOx adsorber systems will have the highest NOx adsorption capability and consequently the longest "lean-to-rich switch" time differential while deteriorated adsorbers with no adsorption capability will have the shortest time differential. Therefore, the NOx adsorber system could be monitored by calibrating the lean-to-rich time differential to indicate a fault when the NOx adsorber system has deteriorated to a level such that the emission thresholds (e.g., 0.2 g/bhp-hr above the NOx emission standard for 2013 and subsequent model year engines) would be exceeded. Honda currently utilizes A/F sensors in a similar manner as described above to monitor the NOx adsorber on a 2003 model year gasoline vehicle.

Since sulfur poisoning reversibly diminishes the performance of the NOx adsorber system, it is imperative that sulfur poisoning be distinguished from a true deteriorated system. Otherwise, perfectly good NOx adsorber systems could erroneously be identified as being bad (i.e., false MILs could occur). Manufacturers of gasoline vehicles with NOx adsorber systems are aware of this issue and are taking various measures to account for adsorber sulfation. These approaches should also work on diesel vehicles. Basically, the monitoring method relies on several phenomena. As sulfation of the adsorber increases, the NOx adsorption capacity of the system progressively decreases. When the NOx adsorption capacity decreases past a predetermined threshold, a desulfation event is intrusively commanded (e.g., with an external heat source or rich fuel mixture) to sufficiently heat up the adsorber for sulfur removal. After desulfation, the adsorber system's NOx capacity is again reevaluated. If the NOx capacity is now below the predetermined threshold, the NOx adsorber is judged good and the previous deteriorated result was due to sulfur poisoning. However, if the NOx capacity is still below the threshold, the NOx adsorber is truly bad and the MIL should be commanded on and a fault code identifying the deteriorated adsorber stored.

The injection system used to achieve desorption of the adsorber could also be monitored with A/F sensors. When the control system injects extra fuel to achieve a rich mixture, the front A/F sensor will respond to the change in fueling and can be used to directly measure whether or not the proper amount of fuel has been injected. If manufacturers employ a NOx adsorber system design that uses only a single A/F sensor downstream of the adsorber for monitoring and control of desorption, the downstream sensor could also be used to monitor the performance of the injection system. As discussed above, the sensor downstream of the adsorber will switch from a lean reading to a rich reading when the stored NO_2 has been released and reduced. If the sensor switches too quickly after rich fueling is initiated, it is an indication that either too much fuel is being injected or the adsorber itself has poor storage capability. Conversely, if the sensor takes too long to switch after rich fueling is initiated, it may be an indication that the adsorber has very good storage capability. However, excessive switch times (i.e., times that exceed the maximum storage capability of the adsorber) would be indicative of an injection system malfunction (i.e., insufficient fuel is being injected) or a sensor malfunction (i.e., the sensor has slow response).

Lastly, monitoring of injection feedback control could be performed using the same strategies discussed for fuel system feedback control monitoring in Section IV.A of this report.

H. PARTICULATE MATTER (PM) FILTER MONITORING

Background

As indicated earlier, the particulate matter (PM) emission standards for the 2007 model year will be reduced by 90 percent from the 2004 model year standards. In order to meet the increasingly stringent standards, manufacturers will likely use aftertreatment devices such as PM filters to achieve the necessary emission levels. PM filters are considered the most effective control technology for the reduction of particulate emissions and can typically achieve PM reductions in excess of 90 percent. In general, a PM filter consists of a filter material that permits exhaust gases to pass through but traps the PM emissions. In order to maintain the performance of the PM filter and the vehicle, the trapped PM must be periodically removed before too much particulate is accumulated and exhaust backpressure reaches unacceptable levels. The process of periodically removing accumulated PM from the filter is known as regeneration and is very important for maintaining low PM emission levels. PM filter regeneration can be passive (i.e., occur continuously during regular operation of the filter), active (i.e., occur periodically after a predetermined quantity of particulates have been accumulated), or a combination of the two. With passive regeneration, oxidation catalyst material is typically placed on the PM filter system to lower the temperature for oxidizing PM. This allows the filter to continuously oxidize trapped PM material during normal driving. In contrast, active systems utilize an external heat source such as an electric heater or fuel burner to facilitate PM filter regeneration. It is projected that virtually all PM filter systems will have some sort of active regeneration mechanism.

One of the key factors that needs to be taken into account for a filter regeneration control system is the amount of soot quantity that is stored in the PM filter (often called soot loading).[20] If too much soot is stored in the PM filter when regeneration is activated, the soot can burn uncontrollably and damage the filter. However, activating regeneration when there is too little trapped soot is also undesirable since there is a minimum amount of soot quantity needed to ensure good burn propagation. Another important factor to be considered in the control system design is the fuel economy penalty involved with filter regeneration. Prolonged operation with high backpressures in the exhaust and too frequent regenerations are both detrimental to fuel economy and durability. Therefore, filter designers will need to carefully balance the regeneration frequency with various conflicting factors. In order to optimize the filter regeneration for

[20] Salvat, O., Marez, P., and Belot, G., “Passenger Car Serial Application of a Particulate Filter System on a Common Rail Direct Injection Diesel Engine,” SAE Paper 2000-01-0473.

these design factors, the control system for the regeneration system is projected to utilize both pressure sensors and temperature sensors to model soot loading among other properties.[20] Through the information provided by these sensors, designers can optimize the PM filter for high effectiveness and maximum durability while minimizing fuel economy and performance penalties.

Proposed Monitoring Requirements

The staff is proposing monitoring requirements that would verify the PM filter's filtering, regeneration, and (for catalyzed PM filters) NMHC conversion performances.

PM Filter Monitoring

The OBD system would be required to indicate a malfunction of the PM filter (e.g., cracks in the filter) when the filtering capability decreased to a point such that the PM emissions exceed a certain emission threshold. For 2010 through 2012 model year engines, the threshold is 0.05 g/bhp-hr, while for 2013 and subsequent model year engines, the threshold is 0.025 g/bhp-hr. Similarly, the proposed regulation would require the OBD system to indicate a fault for an "empty can" (i.e., completely removed/destroyed substrate) or an inappropriately replaced filter (i.e., PM filter assembly replaced by a muffler or a straight pipe).

Additionally, for catalyzed PM filters that are able to convert NMHC emissions, the proposed regulation would require the OBD system to indicate a malfunction when the NMHC conversion efficiency decreases to the point that emissions exceed 2.0 times the NMHC standard. If any malfunction of the NMHC conversion capability cannot cause NMHC emissions to exceed 2.0 times the standard, the OBD system would be required to indicate a malfunction when there is no detectable amount of NMHC conversion.

PM Filter Regeneration Monitoring

Regeneration must be monitored by the OBD system since this process is vital in maintaining the performance of the PM filter. Thus, the staff is proposing to require manufacturers to monitor PM filters for proper performance of the regeneration process. The OBD system would be required to indicate a malfunction when the regeneration frequency increases to a level past the manufacturer's specified regeneration frequency such that NMHC emissions exceed 2.0 times the NHMC standard. If excess regeneration frequency cannot cause emissions to exceed 2.0 times the NMHC standard, the OBD system would be required to indicate a malfunction when the regeneration frequency exceeds the manufacturer's specified design limit for allowable regeneration frequency. The proposed regulation would also require the OBD system to indicate a fault when no regeneration occurs during conditions where the manufacturer designates regeneration to occur.

Additionally, for PM filter systems that use active or intrusive injection (e.g., in-cylinder post-fuel injection) to achieve regeneration of the filter, the OBD system would be required to indicate any malfunction of the injection system that would prevent regeneration of the PM filter.

Regarding feedback-controlled PM filter regeneration systems, staff is proposing that manufacturers indicate a malfunction if the regeneration control system fails to begin feedback control within a manufacturer specified time interval. Manufacturers would also be required to indicate a malfunction if failure or deterioration of components used as part of the feedback control strategy causes the system to go open loop (i.e., stops feedback control) or default operation of the injection system. Lastly, manufacturers would also be required to indicate a malfunction if feedback control has used up all of the adjustment allowed by the manufacturer. Malfunctions that cause delays in starting feedback control and malfunctions that cause open loop operation could either be detected with a regeneration control system specific monitor or with individual component monitors.

Technological Feasibility of Proposed Monitoring Requirements

It is anticipated that manufacturers will not need additional hardware to meet the PM filter monitoring requirements. The same pressure and temperature sensors that are used to control trap regeneration are projected to be used for monitoring. In general, a differential pressure sensor placed across the filter and at least one temperature sensor located near the PM filter are used for the control system. As mentioned earlier, a differential pressure sensor is expected to be used on PM filter systems to prevent damage due to delayed or incomplete regeneration that could lead to excess temperatures. When the pressure sensor senses high pressures, regeneration can be activated. However, while backpressure sensors are a necessary part of the control strategies for the PM filter, pressure sensors alone are not sufficient for proper control and protection of the filter. Staff understands from discussions with engine manufacturers, PM filter suppliers, and consultants, that backpressure by itself does not provide a robust indication of soot loading. To make up for the shortcomings of backpressure sensors, manufacturers will also utilize soot-loading models to predict the loading of the filter and to initiate regeneration. The model will estimate the degree of filter loading by tracking the difference between the modeled engine-out PM (i.e., the emissions that are being loaded on to the filter) and regenerated PM (i.e., the PM that is being burned off the filter due to the vehicle operating conditions and /or active regeneration). If the model indicates the PM filter is heavily loaded but the backpressure sensor does not indicate heavy loading, regeneration will be activated based on the model.

A comprehensive and accurate soot-loading model is necessary for successful monitoring of the PM filter. The proposed monitoring requirements are feasible with further development of the PM filter soot-loading model to make it sufficiently accurate to detect when the actual filter loading inferred from the pressure sensor does not agree with the predicted loading from the soot loading model. The pressure sensor, in combination with the model, could also be used to determine if regeneration is functioning correctly and to evaluate the suitability of the filter for controlling particulate emissions. For example, after a regeneration event, the backpressure should drop significantly since the trapped soot and particles are removed. If backpressure does not drop within the range expected after a regeneration event as predicted by the model, the regeneration did not function correctly (or the filter could have excessive ash loading) and the OBD system would alert the vehicle operator of a problem. Also, backpressure on a normal PM filter should progressively increase as the mass of soot and trapped particles increases. In general, the mass of soot and trapped particles should increase as the mileage traveled or time of operation increases. However, a cracked filter or missing filter may not experience increased backpressure as expected. Therefore, a cracked or missing filter can be detected if the backpressure fails to increase at the rate projected by the soot-loading model. Backpressure increases with both increased soot loading on the filter and with increasing exhaust flowrate (i.e., as engine load increases). To optimize comparison between the soot-loading model and the backpressure sensor, it is important to account for this increase in backpressure due to exhaust flow (e.g., by normalizing the backpressure based on exhaust flow rate).

Manufacturers have expressed a concern, that over time, ash will accumulate on the PM filter, thus altering the soot-loading characteristics of the PM filter. A PM filter with significant ash loading will not drop to as low backpressure levels immediately following a thorough regeneration event and it will load up quicker (because the soot capacity will be reduced by the accumulated ash). If not accounted for, this ash loading could result in inappropriate indication of a fault. Ash loading is a normal byproduct of engine operation (the ash loading is largely a function of oil consumption by the engine and the ash content of the engine oil). Manufacturers could monitor the ash accumulation rate and include that in their soot-loading model. While the ash accumulation rate varies based on the ash content of the engine oil, one manufacturer has indicated it plans on specifying the type of engine oil that must be used so the ash accumulation rate can be accurately accounted for. If the ash accumulation rate significantly exceeds the normal acceptable rate predicted by the model, or the model has determined that the filter has reached its maximum ash loading and the required maintenance is not performed (manufacturers are investigating maintenance intervals and procedures to remove the ash from the filter), a malfunction could then be appropriately indicated.

Lastly, manufacturers have indicated that they are concerned that small differences in crack size or location may generate large differences in tailpipe emission levels, and they are not confident that they can reliably detect all leaks that would result in the emission levels proposed for the malfunction criteria (five times the standard in 2010 through 2012 model years and 2.5 times the standard in 2013 and subsequent model years). Accordingly, the manufacturers have suggested pursuing an alternate malfunction criterion independent of emission level such as a percent of exhaust flow leakage or a specified hole size for a leak. However, staff does not believe that pursuit of such alternate thresholds is appropriate at this time. Manufacturers have not even completed work on initial widespread implementation of PM filters for the 2007 model year, and staff expects substantial refinement and optimization will be made by manufacturers based on their field experience prior to the introduction of this monitor in the 2010 model year.

As mentioned earlier, manufacturers are projected to also use temperature sensors for regeneration control purposes. As an additional benefit, this same sensor could also be used on these systems to monitor active regeneration of the filter. If excess temperatures are seen by the temperature sensor during active regeneration, the regeneration process can be stopped or slowed down to protect the filter. If active regeneration is commanded on and there isn't a sufficient temperature rise in the PM filter system for the amount of soot stored in the filter, the regeneration system is malfunctioning and the OBD system would alert the driver of a problem.

Lastly, monitoring of PM filter regeneration feedback control could be performed using the same strategies discussed for fuel system feedback control monitoring in Section IV.A of this report.

I. EXHAUST GAS SENSOR MONITORING

Background

Exhaust gas sensors (e.g., oxygen sensors, air-fuel ratio (A/F) sensors, NOx sensors) are important to the emission control systems of these heavy duty engines. These sensors are expected to be used by heavy-duty diesel engine manufacturers to optimize their emission control technologies as well as satisfy many of the proposed heavy-duty OBD monitoring requirements, such as catalyst monitoring, NOx adsorber monitoring, and EGR system monitoring. For example, A/F sensors, which provide a precise reading of the actual air-fuel ratio, may be used upstream and downstream of a NOx adsorber both to provide precise closed-loop control of the NOx adsorber system and for OBD monitoring of the system. NOx sensors are also anticipated to be used for optimization of several diesel emission control technologies, such as lean NOx catalysts and selective catalytic reduction (SCR) systems. Since an exhaust gas sensor will be a critical component of a vehicle's emission control system, the proper performance of this component needs to be assured in order to maintain low emissions. Thus, it is important that any malfunction that adversely affects the performance of any of these exhaust gas sensors is detected by the OBD system.

Proposed Monitoring Requirements

The staff is proposing that a manufacturer be required to monitor the sensor performance (i.e., output voltage, resistance, impedance, response rate, and any other characteristic) of all exhaust gas sensors before emissions exceed a certain emission thresholds. For A/F sensors located upstream of the aftertreatment, the staff is proposing that the OBD system be required to indicate a malfunction before emissions exceed 1.5 times the applicable standards. For A/F sensors located downstream of the aftertreatment and for NOx sensors, the thresholds for 2010 through 2012 model year engines are 1.5 times the NMHC standard, 0.3 g/bhp-hr above the NOx standard, and 0.05 g/bhp-hr for PM emissions, while for 2013 and subsequent model year engines, the thresholds are 1.5 times the NMHC standard, 0.2 g/bhp-hr above the NOx standard, and 0.025 g/bhp-hr for PM emissions.

For all exhaust gas sensors, the proposed regulation would also require the OBD system to monitor for circuit continuity and out-of-range faults and faults that would cause the sensor to no longer be sufficient for use for other OBD monitors (e.g., catalyst monitors). Since emission control system performance is essential in meeting the emission standards and maintaining low emissions, malfunctions where the system is unable to optimize this should be detected. Thus, the staff is also proposing that for all exhaust gas sensors, the OBD system would be required to indicate a malfunction when a sensor fault occurs such that an emission control system stops using the sensor as a feedback input. Additionally, for heated exhaust gas sensors, manufacturers would be required to monitor the heater for proper performance as well as circuit continuity faults.

Most of the exhaust gas sensor monitors (e.g., sensor performance) would be required to operate at least once per driving cycle. However, the staff is proposing that for circuit continuity faults, out-of-range values, and faults that prevent the sensor from being used as a feedback input, continuous monitoring would be required. A manufacturer may request Executive Officer approval to disable the continuous exhaust gas sensor monitoring when a sensor malfunction cannot be distinguished from other effects (e.g., disable out-of-range low oxygen sensor monitoring during fuel cut conditions).

Technical Feasibility of Proposed Monitoring Requirements

The light- and medium-duty OBD II regulations have required similar oxygen sensor monitoring since the 1996 model year. The technical feasibility has clearly been demonstrated for these packages. Additionally, A/F sensor monitoring has also been required and demonstrated on these vehicles for many years.

NOx sensors are a recent technology and currently still being developed and improved. However, the staff is expecting manufacturers would design their upstream NOx sensor monitors to be similar the A/F sensor monitors used in light and medium duty gasoline and diesel applications. Monitoring of downstream sensors may require modifications to existing A/F sensor strategies and/or new strategies. Since NOx sensors are projected to only be used for control and monitoring of aftertreatment systems that reduce NOx emissions (e.g., SCR systems), the OBD system would have to distinguish between deterioration of the aftertreatment system and the NOx sensor itself for the reasons discussed below. As the aftertreatment deteriorates, NOx emissions will increase (i.e., the NOx concentration levels in the exhaust increase), and assuming there is no attendant deterioration in the NOx sensor, the NOx sensor will read these increasing NOx levels. As discussed in sections IV.F and IV.G of this report, the increased NOx levels can be the basis for determining a malfunction of the aftertreatment system. However, if the NOx sensor experiences deterioration (has an increasingly slower response rate) along with the aftertreatment system, the sensor may not properly read the increased NOx levels from the malfunctioning aftertreatment system, and the aftertreatment monitor would conclude the malfunctioning aftertreatment system is functioning properly. Similarly the performance of NOx aftertreatment (i.e., level of deterioration of the after treatment system) could affect the results of the sensor monitor. Therefore to achieve robust monitoring of aftertreatment and sensors, the OBD system has to distinguish between deterioration of the aftertreatment system and the NOx sensor. To properly monitor the sensor, it is crucial to account for the effects of aftertreatment performance on the results of a sensor monitor. The NOx sensor monitor has to be conducted under conditions where the aftertreatment performance can either be quantified and compensated for in the monitoring results or its effects can be eliminated.

Using an SCR system as an example, the effects of the SCR performance could be eliminated by monitoring under a steady-state operating condition (i.e., a steady-state engine-out NOx condition). Under a relatively steady-state condition, reductant injection could be "frozen," that is, the reductant injection quantity could be held constant, which would also freeze the conversion efficiency of the SCR system. With SCR performance held constant, engine-out NOx emissions could be intrusively increased by a known amount (e.g., by reducing EGR flow or changing fuel injection timing and allowing the engine-out NOx model to determine the increase in emissions). The resulting increase in emissions would pass through the SCR catalyst unconverted, and the sensor response to the known increase in NOx concentrations could be measured and evaluated. This strategy could be used to detect both response malfunctions (i.e., the sensor reads the correct NOx concentration levels but the sensor reading does not change fast enough to changing exhaust NOx concentrations) and rationality malfunctions (i.e., the sensor reads the wrong concentration level). Rationality malfunctions could be detected by making sure the sensor reading changes by the same amount as the intrusive change in emissions. Lastly, the sensor response to decreasing NOx concentrations could be also be evaluated by measuring the response when the intrusive strategy is turned off and engine out NOx emissions are returned to normal levels. Malfunction criteria could then be determined by correlating sensor response and emission levels from conducting emission tests with sensors having various levels of deterioration.

V. PROPOSED MONITORING SYSTEM REQUIREMENTS FOR GASOLINE/SPARK-IGNITED ENGINES

A. FUEL SYSTEM MONITORING

Background

An important component in emission control on gasoline engines is the fuel system. Proper delivery of fuel is essential to maintain stoichiometric operation and minimize engine out emissions. Proper stoichiometric control is also critical to maximize catalyst conversion efficiency and reach low tailpipe emission levels. As such, thorough monitoring of the fuel system is an essential element in an OBD system.

For gasoline engines, the fuel system generally includes a fuel pump, fuel pressure regulator, fuel rail, individual injectors for each cylinder, and a closed-loop feedback control system using oxygen sensor(s) or air-fuel ratio (A/F) sensor(s). The feedback sensors are located in the exhaust system and are used to regulate the fuel injection quantity to achieve a stoichiometric mixture in the exhaust. If the sensor indicates a rich (or lean) mixture, the system reduces (or increases) the amount of fuel being injected by applying a short term correction to the fuel injection quantity calculated for the current engine operation condition. To account for aging or deterioration in the system such as reduced injector flow, more permanent long term corrections are also learned and applied to the fuel injection quantity for more precise fueling.

Proposed Monitoring Requirements

For gasoline engines, fuel system monitoring has been implemented on light- and medium-duty vehicles from the 1996 model year under the OBD II regulations. For heavy-duty gasoline engines (many of which are the same engine used in lighter medium-duty applications), the system components and control strategies are identical to those used in the light- and medium-duty categories. As such, the monitoring requirements established for light- and medium-duty engines can be directly applied to heavy-duty gasoline engines.

The staff is proposing that the fuel system be continuously monitored for its ability to maintain engine emissions below the standards. Manufacturers would be required to detect a malfunction when the system can no longer achieve this. Since the systems are essentially “self-correcting” and adapt for deterioration, monitoring of the system is accomplished by looking at the adaptive terms (e.g., short term and long term fuel trim) and indicating a fault when the corrections get so large (or reach their adaptive limits) that emissions cannot be maintained below the emission standard. Manufacturers would also be required to verify that the fuel system is in closed-loop operation (e.g., is using the oxygen sensor for feedback and can make changes to the adaptive correction values). Manufacturers have a pre-defined set of criteria that must be satisfied to begin closed-loop operation which typically include a minimum time after engine start, a minimum engine coolant temperature, and some indication that the oxygen sensor is warmed-up and ready. Manufacturers would typically meet this requirement with separate diagnostics that verify each individual criterion is satisfied (which also provides valuable diagnostic information to help repair technicians pinpoint the root cause of the malfunction).

The individual components of the fuel system would also be covered by separate monitoring requirements for oxygen sensors, misfire (for the fuel injectors), and comprehensive components (in systems such as those with electronically-controlled variable speed fuel pumps or electronically-controlled fuel pressure regulators).

Technical Feasibility of Proposed Monitoring Requirements

For gasoline engines, the light- and medium-duty OBD II regulations have required identical fuel system monitoring since the 1996 model year. Over 84 million cars have been built and sold in the U.S. to these fuel system monitoring requirements including medium-duty vehicles which utilize the exact same gasoline engines that are also used in some heavy-duty vehicle applications. The technical feasibility has clearly been demonstrated for these packages.

B. MISFIRE MONITORING

Background

One of the primary causes of catalyst degradation is engine misfire, which is the lack of combustion due to the absence of spark or poor fuel metering, among other causes. When misfire occurs, unburned fuel and air are pumped into the catalyst, greatly increasing its operating temperature (where the temperature can soar to above 900 degrees Celsius). This problem is usually most severe under high load, high speed engine operating conditions, causing irreversible damage to the catalyst. Though the durability of catalysts has been improving, most are unable to sustain continuous operation at such high temperatures. Engine misfire also contributes to excess emissions, especially when the misfire is present during engine warm-up and the catalyst has not reached its operating temperature.

Proposed Monitoring Requirements

Accordingly, for gasoline engines, the staff is proposing continuously monitoring for engine misfire at all positive torque engine speeds and load conditions. Additionally, manufacturers would be required to identify a misfiring cylinder or indicate if multiple cylinder misfiring is occurring (through the storage of the appropriate fault codes). With regards to catalyst-damaging misfire, manufacturers would be required to determine the level (i.e., percentage) of misfire per 200 revolution increments (e.g., two seconds at 6000 rpm) for each engine speed and load condition that would result in a temperature that causes catalyst damage. The proposed regulation would establish a specific means of determining the temperature at which catalyst damage occurs. With regards to misfire that can cause excess emissions, manufacturers would be required to determine the level of misfire per 1000 revolution increments that would result in emissions exceeding 1.5 times the applicable standards. To establish this percentage of misfire, manufacturers would utilize misfire events occurring at equally spaced, complete engine cycle intervals, across randomly selected cylinders throughout each 1000-revolution increment. The staff is also proposing to set a lower limit on the level of misfire that is required to be detected (i.e., five percent for misfire causing catalyst damage, and one percent for misfire causing emissions to exceed 1.5 times the standards), due to increased difficulty in diagnosing misfire at such low percentages.

Although the proposal would require misfire monitoring to occur continuously for gasoline engines, the proposed regulation would allow manufacturers to temporarily disable misfire monitoring during certain operating conditions where misfire cannot be reliably detected. These conditions include driving on rough roads, during manual transmission gear changes, and during extremely rapid throttle changes. Manufacturers that want to disable misfire monitoring during conditions not specifically stated in the proposed regulation would be required to request Executive Officer approval of such disablement. Some manufacturers may request disablement during a certain amount of time from engine start-up (end of crank), since they may contend that such conditions may cause unreliable misfire detection. The staff, however, is concerned that misfire could occur during start-up (i.e., during cold start when the engine can run rough) and then cease once warming of the engine has occurred. Such misfire problems would significantly impact emissions, since the catalyst would not have reached its operating temperature. Thus, the proposed regulation would require misfire monitoring to occur no later than the end of the second crankshaft revolution after engine start-up.

Technical Feasibility of Proposed Monitoring Requirements

For gasoline engines, the light- and medium-duty OBD II regulations have required identical misfire monitoring requirements since the 1996 model year. One of the most reliable methods for detecting misfire that has been demonstrated is the use of a crankshaft position sensor, which would measure the fluctuations in engine angular velocity and determine if misfire exists, and a camshaft position sensor, which can be used to identify the misfiring cylinder. This method has been shown to be technically feasible for misfire monitoring on light- and medium-duty vehicles.

C. EXHAUST GAS RECIRCULATION (EGR) SYSTEM MONITORING

Background

Exhaust gas recirculation (EGR) is one of the most effective emission control technologies for reducing NOx emissions in vehicles today. Generally, NOx emissions are formed under high combustion chamber temperature and pressure conditions. EGR systems redirect spent combustion gases from the exhaust stream to the intake system to dilute the oxygen concentration and increase the heat capacity of the air/fuel charge. This effectively reduces the combustion temperature, which results in lower levels of NOx emissions. EGR systems can involve many components to ensure accurate control of EGR flow, including valves, valve position sensors, and actuators.

Proposed Monitoring Requirements

The EGR system would need to be monitored to ensure that the appropriate amount of EGR flow reaches the intake system. The staff is proposing that manufacturers be required to indicate an EGR system malfunction when the EGR flow rate increases or decreases to a point where emissions exceed 1.5 times the applicable standards. While decreased EGR flow can cause increased emissions, excessive EGR flow can also cause increased emissions and driveability problems. Manufacturers would be required to monitor the EGR flow rate at least once per driving cycle in which the monitoring conditions are met. If a malfunctioning EGR system (with a reduced flow or excessive flow fault) cannot cause emissions to exceed the emission threshold of 1.5 times the applicable standards, a manufacturer would only be required to perform functional monitoring of the malfunction of concern (e.g., indicate a malfunction when no detectable amount of EGR flow is detected). The individual electronic components utilized by the EGR system would be monitored under the comprehensive components monitoring requirements.

Technical Feasibility of Proposed Monitoring Requirements

The light- and medium-duty OBD II regulations have required identical EGR system monitoring since the 1996 model year. Manufacturers have been detecting malfunctions of EGR flow rate generally by looking at the change in fuel trim or manifold pressure under conditions when the EGR system is active. The technical feasibility of EGR monitoring has already been demonstrated for these applications.

D. COLD START EMISSION REDUCTION STRATEGY MONITORING

Background

The largest portion of exhaust emissions from gasoline vehicles is generated during the brief period following a cold start before the engine and catalyst have warmed up. In order to meet increasingly stringent emission standards, manufacturers are developing hardware and associated control strategies to reduce these emissions. Most efforts are centering around reducing catalyst warm-up time. A cold catalyst is heated mainly by two mechanisms - heat transferred from the exhaust gases and heat that is generated in the catalyst as a result of the catalytic reactions.

Manufacturers are implementing various hardware and control strategies to quickly light off the catalyst (i.e., reach the catalyst temperature at which 50 percent conversion efficiency is achieved). Most manufacturers use substantial spark retard and/or increased idle speed to maximize the heat available in the exhaust following a cold start to quickly light off the catalyst. However, customer satisfaction and safety (i.e., vehicle driveability and engine idle quality) limit the amount of spark retard or increased idle speed that a manufacturer will use to accelerate catalyst light off. On a normally functioning vehicle, engine speed drops when the spark is retarded, therefore causing the idle speed control system to compensate and allow more airflow (with a corresponding increase in fuel) to the engine in order to maintain idle speed stability during spark retard. Since idle quality is given a high priority, spark retard is typically limited to an extent that the idle control system can quickly respond to and maintain idle quality. Conversely, a deteriorated or poorly responding idle control system would reduce the capability of the engine to compensate and may cause the on-board computer to command less spark retard than would normally be achieved for a properly functioning system, thereby causing delayed catalyst light off and higher emissions.

Though the proposed regulation would require monitoring of the idle control system and monitoring of the ignition system by the misfire monitor, the idle control system is normally monitored only after the engine has warmed up, and malfunctions that occur during cold start may not be detected by the OBD system, yet have significant emission consequences.

Additionally, given the escalating cost of precious metals, there is an industry trend to minimize their use in catalysts. To compensate for the reduction in catalyst performance, manufacturers will likely employ increasingly more aggressive cold start emission reduction strategies. It is crucial that these strategies be successful and properly monitored in order to meet the new, more stringent emission standards and to maintain low emissions in-use.

Proposed Monitoring Requirements

Considering the issues outlined above, the staff is proposing a requirement to monitor the individual components used to implement cold start emission reduction strategies. This would ensure that the target conditions necessary to reduce emissions or catalyst light-off time are indeed achieved and emissions do not exceed 1.5 times the emission standard. These components would need to be monitored while the strategy is active. For example, if the target idle speed for catalyst light-off could not be achieved or maintained adequately to maintain emissions below 1.5 times the standard, a malfunction would need to be indicated. Similarly, if the target spark retard necessary for catalyst light-off could not be achieved due to an idle control system malfunction, a fuel system malfunction, or any other malfunction, a fault would need to be indicated.

Technical Feasibility of Proposed Monitoring Requirements

Monitoring techniques that are projected to be used for cold start monitoring strategies would be similar to those already outlined during the light- and medium-duty OBD rulemaking, which mainly involve software modifications. For example, if spark retard is used during cold starts, the commanded amount of spark retard would have to be monitored if the amount of spark retard can be restricted by external factors such as idle quality or driveability. This can be done with software algorithms that compare the actual overall commanded final ignition timing with the threshold timing that would result in emissions that exceed 1.5 times the standard. Cold start strategies that always command a predetermined amount of ignition retard independent of all other factors and do not allow idle quality or other factors to override the desired ignition retard do not require monitoring of the commanded timing. Other methods to ensure the actual timing has been reached include verifying other factors such as corresponding increases in mass air flow and idle speed indicative of retarded spark combustion. Since mass air flow and idle speed are both currently used by the engine control system and the OBD system, only minor software modifications should be required to further analyze these signals while the cold start strategy is invoked.

As required for other OBD monitors, the stored fault code would, to the fullest extent possible, be required to pinpoint the likely cause of the malfunction to assist technicians in diagnosing and repairing these malfunctions. The proposal would also allow a manufacturer to develop calibrations on representative vehicles and apply the calibrations to the remainder of the product line.

E. SECONDARY AIR SYSTEM MONITORING

Background

Secondary air systems, which are expected to be utilized only on gasoline vehicles, are used to reduce cold start exhaust emissions of hydrocarbons and carbon monoxide. Although many of today's vehicles operate near stoichiometric (where the amount of air is just sufficient to completely combust all of the fuel) after a cold engine start, more stringent emission standards may require secondary air systems, generally in combination with a richer than stoichiometric cold start mixture, to quickly warm up the catalyst for improved cold start emission performance. Secondary air systems typically consist of an electric air pump, various hoses, and check valves to deliver outside air to the exhaust system upstream of the catalytic converters. This system usually operates only after a cold engine start for a brief period of time. When the electric air pump is operating, fresh air is delivered to the exhaust system and mixes with the unburned fuel at the catalyst, so that the fuel can burn and rapidly heat up the catalyst. Problems with the secondary air systems that may be found in the field include corroded check valves, damaged tubing and hoses, and malfunctioning air switching valves. Given the importance of properly functioning secondary air systems to emission performance, monitoring is needed.

Proposed Monitoring Requirements

The secondary air system would have to be monitored to verify secondary air delivery to the exhaust system during cold engine starts when it is normally active. Thus, the staff is proposing that manufacturers be required to monitor proper functioning of the secondary air delivery system including all air switching valves. Specifically, a manufacturer would be required to indicate a malfunction prior to a decrease from the manufacturer's specified air flow during normal operation (e.g., during vehicle warm-up following engine start) that would cause a vehicle's emissions to exceed 1.5 times the applicable standards. Manufacturers would be required to monitor the secondary air system at least once per driving cycle in which the monitoring conditions are met. If a malfunctioning secondary air system cannot cause emissions to exceed the emission threshold of 1.5 times the applicable standards, a manufacturer would only be required to perform functional monitoring of the system by indicating a malfunction when no detectable amount of air flow is delivered during normal operation. The individual electronic components utilized by the secondary air system would be monitored under the comprehensive components monitoring requirements.

Technical Feasibility of Proposed Monitoring Requirements

In order for the OBD system to effectively monitor the secondary air system when it is normally active, A/F sensors would most likely be required. These sensors are currently installed on many new cars and their implementation is projected to increase in the future as more stringent emission standards are phased in. A/F sensors are useful in determining air-fuel ratio over a broader range than conventional oxygen sensors and are especially valuable for controlling fueling in lean-burn engines and other engine designs that require very precise fuel control. They would be useful for secondary air system monitoring because of their ability to determine air-fuel ratio accurately, which would enable correlating the amount of secondary airflow needed to keep emissions below 1.5 times the tailpipe emission standard to the air-fuel ratio.

F. CATALYST MONITORING

Background

Three-way catalysts are one of the most important emission-control components utilized by gasoline engines. They consist of ceramic or metal honeycomb structures (i.e., “substrates”) coated with precious metals such as platinum, palladium, or rhodium. These precious metals are dispersed within an alumina washcoat containing ceria, and the substrates are mounted in a stainless steel container in the vehicle exhaust system. Three-way catalysts are so designated because they are capable of simultaneously oxidizing HC and CO emissions into water and carbon dioxide, and of reducing NOx emissions (by reacting with CO and hydrogen) into elemental nitrogen, carbon dioxide, and water.

This three-way conversion activity only takes place efficiently, however, when the fuel system operates at stoichiometric (i.e., the air/fuel ratio where there is just the required amount of air to completely burn all of the fuel in the engine). Manufacturers achieve and maintain stoichiometric fuel delivery by incorporating closed-loop fuel control systems that utilize an exhaust gas oxygen sensor to provide feedback on the status of the air-fuel ratio being achieved. Most closed-loop fuel control systems actively cycle the air-fuel ratio slightly above and below the stoichiometric point to maximize three-way catalyst conversion efficiency. The precious metals are used to temporarily retain the HC, CO, and NOx molecules in the catalyst and promote the chemical reactions while the ceria in the washcoat is used to store and release oxygen that is needed to complete the reactions. Oxygen is stored in the catalyst during the lean portion of the fuel system’s cycling (i.e., when the air-fuel ratio is slightly higher than stoichiometric) and is released during the rich excursion.

While improvements to catalysts over the years have increased their durability, they are still subject to high temperature deterioration that occurs when excess air and fuel enter the catalyst. This can be caused by misfire (i.e., unburned fuel and air that are pumped into the catalyst) among other factors, and will result in reduced catalyst conversion efficiency. Catalyst performance can also deteriorate due to catalyst deactivation from poisoning (e.g., lead, phosphorus). Additionally, catalysts can also fail due to mechanical problems, such as excessive vibration or damage to the catalyst itself.

Proposed Monitoring Requirements

Due to the importance of the catalyst system in a vehicle's emission control system, the staff is proposing monitoring for proper catalyst system performance. Specifically, manufacturers would be required to indicate a catalyst malfunction when the catalyst system's conversion capability decreases to a point that emissions exceed 1.75 times the applicable HC or NOx standards. The staff is proposing that the catalyst monitor run at least once per driving cycle. Manufacturers that utilize multiple catalyst systems would only be required to conduct catalyst OBD monitoring on catalysts exposed to untreated exhaust gas (except for bypass catalysts). These catalysts are most likely to be damaged and would provide the earliest indication of a catalyst system problem. Replacement of these catalysts alone would also restore a high conversion efficiency to the system since the majority of emissions occur during a cold start and the forward catalysts are the most important for controlling cold start emissions.

When determining the proper OBD malfunction threshold for catalysts, manufacturers would progressively deteriorate or "age" catalysts (by replicating excessive temperature conditions via oven aging or misfire aging) to the point where emissions exceed 1.75 times the standard. Thus, the staff is also proposing specific requirements for catalyst aging and determining the malfunction thresholds for the catalyst monitor. Specifically, manufacturers would be required to use deterioration methods that more closely represent real world deterioration, thereby ensuring that the MIL would illuminate at the appropriate emission level during real world operation. The proposal would further require that the catalyst system be aged as a whole (i.e., manufacturers would simultaneously age the monitored and unmonitored catalysts) to the malfunction criteria. This accounts for the fact that the unmonitored catalysts could also experience some real world deterioration. However, manufacturers that use fuel shutoff to misfiring cylinders in order to minimize catalyst over-temperature would be allowed to age the monitored catalyst to the malfunction criteria and the unmonitored catalysts to the end of the useful life. Such systems are less likely to be subjected to extreme temperatures, so they would likely age with the monitored catalyst experiencing most of the deterioration.

Technical Feasibility of Proposed Monitoring Requirements

A common method used for estimating catalyst efficiency is to measure the catalyst's oxygen storage capacity. This monitoring method is utilized by all current light- and medium-duty gasoline vehicles since the OBD II regulation was first fully implemented in the 1996 model year. Generally, as the catalyst's oxygen storage capacity decreases, its conversion efficiency of HC and NOx also decreases. With this strategy, a catalyst malfunction would be detected when its oxygen storage capacity has deteriorated to a predetermined level. Manufacturers could determine this by utilizing the information from the upstream oxygen sensor and a second oxygen sensor located downstream of the monitored portion of the catalyst (this second sensor is also used for trimming the front sensor to maintain precise fuel control). By comparing the level of oxygen measured by the second sensor with that measured by the primary sensor located upstream of the catalyst, manufacturers determine the oxygen storage capacity of the catalyst and thus, estimate the conversion efficiency. With a properly functioning catalyst, the second oxygen sensor signal will be fairly steady since the fluctuating oxygen concentration (due to the fuel system cycling about stoichiometric) at the inlet of the catalyst is damped by the storage and release of oxygen in the catalyst. When a catalyst is deteriorated, such damping is reduced, causing the frequency and peak-to-peak voltage of the second oxygen sensor to simulate the signal from the front oxygen sensor because the catalyst is no longer capable of storing and releasing oxygen.

G. EVAPORATIVE SYSTEM MONITORING

Background

In addition to emissions from a vehicle's tailpipe, ARB is concerned about emissions from a vehicle's evaporative system. Emissions that vent to the atmosphere through leaks in the evaporative system (e.g., disconnected evaporative system hoses) can be many times the evaporative emission standards. Additionally, evaporative purge system defects such as deteriorated vacuum lines, damaged canisters, and non-functioning purge control valves may occur, also resulting in high evaporative emissions.

Proposed Monitoring Requirements

Thus, the staff is proposing to require manufacturers to monitor the evaporative system for leaks equal to or greater than a 0.090 inch diameter hole. The 0.090 inch leak monitoring requirement is intended to detect larger leaks such as split or disconnected evaporative system hoses or loose/missing gas caps. With regards to the orifice shape and length, the staff proposes the use of a specific orifice supplied by O'Keefe Controls Corporation, a manufacturer and supplier of precision orifices used by many in the industry. Orifices with equivalent specifications from other suppliers would also be acceptable. Additionally, the proposed regulation would require manufacturers to verify the purge flow from the vehicle canister system (i.e., to verify that the purge flow is actually reaching the engine and not venting into the atmosphere).

While the OBD II regulations have required leak detection for 0.020 inch leaks beginning with 2000 model year, light- and medium-duty manufacturers have found that fuel tanks larger than 25 gallons are extremely difficult to monitor to the leak sizes required by the OBD II regulation. To address this issue, the OBD II regulation contained a provision that allowed manufacturers to revise the leak size requirements for vehicles equipped with larger fuel tanks provided the manufacturer demonstrate the need for this allowance. Given that the vast majority, if not all, of the gasoline tanks in the heavy-duty industry are likely larger than 25 gallons, the staff evaluated the capability of the medium-duty manufacturers with large tanks and has accordingly proposed heavy-duty OBD monitoring only to 0.090 inch leaks in lieu of 0.020 inch leaks. While a 0.090 inch leak is significantly larger than what is currently being done on light- and medium-duty vehicles, current practices in the heavy-duty industry allow for tremendous variation and modification of the evaporative emission control system including the size, shape, and location of the tank. These variations have a significant impact on the ability of the monitor to accurately detect leaks. Accordingly, the 0.090 inch size was selected to compromise between reasonable leak detection and the ability to calibrate a robust monitor that could handle some variation in evaporative system configuration.

Technical Feasibility of Proposed Monitoring Requirements

As mentioned above, the OBD II regulation has required monitoring of evaporative system leaks as small as 0.020 inches on light- and medium-duty vehicles for several years. These include medium-duty applications such as incomplete trucks and engine dynamometer certified configurations similar (and in many cases, identical) to the configurations used on heavy-duty applications. Applications successfully meeting the OBD II requirements have also included dual tank configurations as well as applications with tanks up to 55 gallons. Manufacturers have successfully implemented these requirements by utilizing monitoring techniques that create either a vacuum or pressurized condition in the fuel tank and evaporative system and check the change in vacuum/pressure over time. In general, these systems require the addition of an evaporative system pressure sensor and a canister vent valve capable of closing the vent line. In some cases, manufacturers have elected to add pressure pumps to generate a positive pressure in lieu of using the engine as a vacuum source. Further, in a few cases, manufacturers have implemented changes to the on-board computer to allow a portion of the control module to remain "on" even while the engine is off and monitor the natural vacuum and pressure fluctuations that occur in the system due to heating and cooling of the gasoline in the tank. Evaporative systems that have too large of a leak will be unable to build or hold pressure or vacuum for a sufficient amount of time and can be distinguished from systems without a leak.

Heavy-duty gasoline applications are expected to use near identical, if not identical, evaporative system components and the staff is not aware of any reason the existing monitoring techniques would not continue to work on heavy-duty applications. Further, by limiting the monitoring to leaks of 0.090 inch or larger, the monitor should be less sensitive to tank location, size, shape, and other factors that have much larger influences on robustly detecting very small leaks. It is expected that gasoline engine manufacturers will need to impose tighter restrictions on their engine purchasers than they currently do with regards to tank specifications and evaporative system components.

H. EXHAUST GAS SENSOR MONITORING

Background

Exhaust gas sensors (e.g., oxygen sensors, air-fuel ratio (A/F) sensors) are important to the emission control system of these engines. In addition to maintaining the air-fuel ratio at stoichiometric, which helps achieve the lowest engine emissions, these sensors are also used for enhancing the performance of several emission control technologies (e.g., catalysts, EGR systems). Many modern vehicles traditionally perform fuel control with an oxygen sensor feedback system. In order for the emission control system to operate most efficiently, the air-fuel ratio must remain within a very narrow range (less than one percent deviation) around the stoichiometric ratio. Oxygen sensors are typically located in the exhaust system upstream and downstream of catalytic converters. The front or upstream oxygen sensor is generally used for fuel control, while the rear or downstream oxygen sensor is generally used for adjusting the front oxygen sensor as it ages and for monitoring the catalyst system. Many vehicles use A/F sensors, which provide a precise reading of the actual air-fuel ratio, in lieu of conventional oxygen sensors for fuel control and catalyst monitoring. Both of these sensors are expected to be used by the heavy-duty manufacturers to optimize their emission control technologies as well as satisfy many of the proposed heavy-duty OBD monitoring requirements, such as fuel system monitoring, catalyst monitoring, and EGR system monitoring. Since an exhaust gas sensor can be a critical component of a vehicle's fuel and emission control system, the proper performance of this component needs to be assured in order to maintain low emissions. Thus, it is important that any malfunction that adversely affects the performance of any of these exhaust gas sensors is detected by the OBD system.

Proposed Monitoring Requirements

The staff is proposing that a manufacturer be required to monitor the output voltage, resistance, impedance, response rate, and any other characteristic of an exhaust gas sensor that can affect emissions and/or other diagnostics. This requirement applies to both primary sensors (which are used for fuel control) and secondary sensors (which are used for control/feedback and monitoring of certain emission control technologies). Since proper fuel control and emission control system performance is essential in meeting the emission standards and maintaining low emissions, malfunctions where the system is unable to optimize these functions should be detected. Thus, manufacturers would also be required to indicate a malfunction when a sensor fault occurs such that the fuel system or an emission control system stops using the sensor as a feedback input. Additionally, for heated exhaust gas sensors, manufacturers would be required to monitor the heater for proper performance as well as circuit continuity faults.

Most of the exhaust gas sensor monitors (e.g., response rate) would be required to operate at least once per driving cycle. However, the staff is proposing that for circuit continuity faults, out-of-range values, and faults that prevent the sensor from being used as a feedback input, continuous monitoring would be required. While fuel system monitors may already be able to identify some of the oxygen and A/F sensor malfunctions, fuel system faults are generally one of the most difficult faults to diagnose and repair due to the substantial number of possible causes. As such, these requirements would help to pinpoint the oxygen or A/F sensor as the malfunctioning component if a circuit problem is occurring. A manufacturer may request Executive Officer approval to disable the continuous exhaust gas sensor monitoring when a sensor malfunction cannot be distinguished from other effects (e.g., disable out-of-range low oxygen sensor monitoring during fuel cut conditions).

Technical Feasibility of Proposed Monitoring Requirements

The light- and medium-duty OBD II regulations have required similar oxygen sensor monitoring since the 1996 model year. The technical feasibility has clearly been demonstrated for these packages. Additionally, A/F sensor monitoring has also been required and demonstrated on these vehicles for many years.

VI. PROPOSED MONITORING SYSTEM REQUIREMENTS FOR ALL VEHICLES

A. VARIABLE VALVE TIMING AND/OR CONTROL (VVT) SYSTEM MONITORING

Background

Variable valve timing (VVT) and/or control systems are used primarily to optimize engine performance and have many advantages over conventional valve control. Instead of opening and closing the valves by fixed amounts, VVT controls can vary the valve opening and closing timing (as well as lift amount in some systems) depending on the driving conditions (e.g., high engine speed and load). This feature permits a better compromise between performance, driveability, and emissions than conventional systems. With more stringent NOx emission standards being phased in, more vehicles are anticipated to utilize VVT. By utilizing VVT to retain some exhaust gas in the combustion chamber to reduce peak combustion temperatures, NOx emissions are reduced.

Proposed Monitoring Requirements

Since valve timing can directly affect exhaust emissions, the staff is proposing specific requirements for monitoring VVT and/or control systems. In addition to monitoring the individual electronic components used in the VVT system, manufacturers would be responsible for detecting target errors and slow response malfunctions of these systems. For target error and slow response malfunctions, the diagnostic system would be required to detect malfunctions when the actual valve timing and/or lift deviates from the commanded valve timing and/or lift such that 1.5 times the applicable emission standard would be exceeded. For VVT and/or control systems that cannot cause emissions to exceed 1.5 times the standard, manufacturers would still be required to monitor the system for proper functional response under the comprehensive component requirements.

Technical Feasibility of Proposed Monitoring Requirements

VVT systems are already in general use in light- and some medium-duty applications. Further, under the OBD II requirements, such systems have been monitored for proper function on the applications that have used VVT systems since the 1996 model year. More recently light and medium manufacturers have designed monitoring strategies to detect VVT system malfunctions that cause emissions to exceed an emission threshold. Such strategies include the use of the crank angle sensor and camshaft position sensor to confirm that the valve opening and closing occurs within an allowable tolerance of the commanded crank angle. By calculating the difference between the commanded valve opening crank angle and the achieved valve opening crank angle, a diagnostic algorithm could differentiate between a malfunctioning system with too large of an error and a properly functioning system with very little to no error. By calibrating the size of this error (or integrating it over time), manufacturers could design the system to indicate a malfunction prior to the required emission threshold. In the same manner, system response can be measured by monitoring the length of time necessary to achieve the commanded valve timing. To ensure adequate resolution between properly functioning systems and malfunctioning systems, most manufacturers only perform this type of check when a large enough "step change" in commanded valve timing occurs.

B. ENGINE COOLING SYSTEM MONITORING

Thermostat

Manufacturers typically use a thermostat to block the flow of coolant within the engine block during cold starts to promote rapid warming of the engine. As the coolant approaches a specific temperature, the thermostat begins to open and allows circulation of coolant through the radiator. The thermostat then acts to regulate the coolant to the specified temperature. If the temperature rises above the regulated temperature, the thermostat opens further to allow more coolant to circulate, thus reducing the temperature. If the temperature drops below the regulated temperature, the thermostat partially closes to reduce the amount of coolant circulating, thereby increasing the temperature. If a thermostat malfunctions in such a manner that it does not adequately restrict coolant flow during vehicle warm-up, an increase in emissions could occur do to the prolonged operation of the vehicle at temperatures below the stabilized, warmed-up value (i.e., due to cold start engine control strategies). The emission impact may vary considerably from one manufacturer to another based on cooling system design and air-fuel control strategies; however, it is generally acknowledged that the component can impact emissions significantly, particularly at lower ambient temperatures (e.g., 50 degrees Fahrenheit). Further, since the engine coolant temperature would potentially be used as an enable criterion for other OBD diagnostics, if the vehicle's coolant temperature does not reach a manufacturer-specified warmed-up value, several diagnostics may effectively be permanently disabled from identifying other emission-related malfunctions.

The staff is proposing that manufacturers be required to monitor the thermostat for proper performance. Manufacturers would be required to detect malfunctions if, within a certain time period after engine start, the engine coolant temperature does not achieve the highest temperature required to enable other OBD monitors or warm up to within 20 degrees Fahrenheit of the manufacturer-specified thermostat regulating temperature. The time period threshold(s) (i.e., the time after engine start when the thermostat would be considered malfunctioning) would be a function of starting engine coolant temperature and vehicle operating conditions that contribute to coolant temperature warm-up. Regarding the latter requirement (i.e., malfunction detection when the coolant temperature does not warm up to within 20 degrees Fahrenheit of the thermostat regulating temperature), subject to Executive Officer approval, a manufacturer would be permitted to monitor the thermostat for a larger deviation from the nominal warmed-up temperature if it adequately demonstrates that a thermostat operating at the lower temperature will not cause an emission increase of 50 or more percent of any of the applicable standards (e.g., a 50 degree Fahrenheit emission test). Manufacturers would be required to submit test data and/or an engineering analysis of the coolant temperature-based modifications to the engine control strategies to support their request. The thermostat monitoring requirement could be satisfied by verifying that the coolant temperature reaches a stabilized value after a period of engine operation, taking into account engine load and coolant temperature at engine start.

Some of the manufacturers' largest vehicles require a high capacity passenger compartment heating system. In cold weather, use of the heaters may not allow sufficient coolant temperature to be achieved in order to avoid illumination of the malfunction light, even when the thermostat is functioning normally. As a result, manufacturers have been forced to select very restrictive monitoring conditions that may not be frequently encountered in-use to ensure an accurate decision.

Therefore, the staff is proposing that vehicles that do not reach the temperatures specified by the malfunction criteria would be allowed to use alternate malfunction criteria and/or temperatures that are a function of coolant temperature at engine start. Manufactures could use this provision upon demonstrating that a properly operating system does not reach the specified temperatures and that the possibility for cooling system malfunctions to go undetected and disable other OBD monitors is minimized to the extent technically feasible.

<u>Engine Coolant Temperature Sensor</u>

Manufacturers generally utilize engine coolant temperature (ECT) as an input for many of the emission-related engine control systems. For gasoline engines, the ECT is often one of the most important factors in determining if closed-loop fuel control will be allowed by the engine's powertrain computer. If the engine coolant does not warm up sufficiently, closed-loop fuel control is usually not allowed and the vehicle remains in open-loop fuel control. Since open-loop fuel control does not provide precise fuel control, this results in increased emission levels. Diesel engines generally use ECT to initiate closed-loop control of some emission control systems, such as EGR systems.

Similar to closed-loop fuel control on gasoline engines, if the coolant temperature does not warm up, closed-loop control of these emission control systems will usually not begin, which will also result in increased emissions. For both gasoline and diesel engines, ECT would potentially be used to enable many of the diagnostics that are required by the heavy-duty OBD regulation (e.g., an OBD monitor would not run until the coolant temperature is above or below a certain temperature to ensure accurate detection capability). If the ECT sensor malfunctions and remains at a low or high reading, many diagnostics would not be enabled.

The staff is proposing that manufacturers be required to monitor the ECT sensor for proper performance. Manufacturers would be required to monitor the sensor to ensure that the vehicle achieved the highest minimum temperature needed for closed-loop control of all emission control systems (e.g., fuel system, EGR system) on gasoline and diesel vehicles within an Executive Officer-approved time after start-up, which would be based on ECT at start-up and/or intake air temperature. The Executive Officer would approve the time interval upon determining that the data and/or engineering evaluation submitted by the manufacturer supports the specified times. Vehicles that do not utilize engine coolant temperature to enable closed-loop control of any emission control system would be exempted from this monitoring requirement.

Additionally, manufacturers would be required to monitor the coolant temperature sensor for rationality, electrical, and out-of-range failures. Since the ECT sensor is essential for both fuel and spark timing control as well as for other OBD monitors, the rationality monitor needs to be more capable in detecting sensor faults than rationality monitors of non-temperature sensors (which follow the comprehensive component monitoring requirements). Accordingly, the proposed regulation would require that rationality monitoring for ECT sensors identify ones that read inappropriately low or high (and thus, disable or delay operation of other monitors). Generally, however, manufacturers may be exempt from rationality monitoring of low sensor readings that disable other OBD monitors, since the OBD monitor for the thermostat (described above) would generally be designed to detect this fault. Additionally, manufacturers may be exempt from monitoring ECT sensors stuck at high temperature regions: (1) where the MIL would be illuminated for default mode operation (e.g., overtemperature protection strategies), or (2) that fall within the red zone of the temperature gauge in cases where the ECT sensor is used for both the OBD system and the temperature gauge.

Technical Feasibility of Proposed Monitoring Requirements

The light- and medium-duty OBD II regulations have required identical ECT sensor and thermostat monitoring since the 1996 model year. While the technical feasibility of the proposed requirements has clearly been demonstrated on light- and medium-duty vehicles, the engine manufacturers have expressed concerns that monitoring of the cooling system on heavy-duty applications creates unique and possibly insurmountable challenges. Generally, the cooling system is divided into two cooling circuits connected by the thermostat. The two circuits are the engine circuit and the radiator circuit.

Manufacturers contend that they do not know what types of devices will be added to the cooling system when the vehicle is manufactured or the vehicle is put into service. They are concerned that the unknown devices can add/remove unknown quantities of heat to/from the system which will prevent them from reliably predicting proper system behavior (e.g., warm up) and indicating a fault when the system is malfunctioning (e.g., not warming up as expected).

Staff believes concerns regarding devices on the radiator side of the system are not warranted because a properly functioning thermostat does not allow flow through the radiator during warm-up and these devices affecting the radiator circuit can only affect coolant temperature when there is significant flow through the radiator (i.e., after the engine is warmed-up and the thermostat is open allowing coolant to flow through the radiator).

Staff recognizes the manufacturers' concerns that devices in the engine circuit (e.g., passenger compartment heaters) can affect the warm-up of the system. However, light- and medium-duty manufacturers have demonstrated robust thermostat monitoring with high capacity passenger heaters in the cooling system. In order to design a robust cooling system monitor, the manufacturer has to know the maximum rate of heat loss due to the heater. Engine manufacturers have control over this by providing limits on such devices in the build specifications provided to the vehicle manufacturers. In some cases, an engine manufacturer might need multiple build specifications with corresponding thermostat monitoring calibrations to accommodate the ranges of heater capacities that are needed when a given engine is used in a range of vehicle applications (e.g., a local delivery truck with a passenger compartment for two people and a small capacity heater versus a bus with a passenger compartment for 20 people and a large capacity heater). The vehicle manufacturer would then select the appropriate calibration for the engine when it is installed in the vehicle. The engine manufacturers have nonetheless requested limited enable conditions for the thermostat monitor (e.g., to disable the thermostat monitor below 50 °F) to minimize their resources spent calibrating the thermostat monitor. While this may mitigate the manufacturers concerns', it is unacceptable because it would result in no monitoring of the thermostat during cold ambient conditions for regions that have prolonged cold ambient conditions. In such regions, a vehicle could experience a thermostat malfunction with no indication to the vehicle operator with consequent disablement of the monitors that require warmed-up coolant temperate to execute.

C. CRANKCASE VENTILATION (CV) SYSTEM MONITORING

Background

Combustion in each cylinder is achieved by drawing air and fuel into the cylinder, compressing the mixture with a piston, and then igniting the mixture. After the combustion event, the mixture is exhausted from the cylinder with another stroke of the piston. However, during the combustion process, exhaust gases can escape past the piston into the crankcase and subsequently to the atmosphere. The CV system is used to remove these gases (known as “blow-by”) from the crankcase and direct them to the intake manifold to be burned by the engine. The CV system generally consists of a fresh air inlet hose, a crankcase vapor outlet hose, and a CV valve to control the flow through the system. Fresh air is introduced to the crankcase via the inlet (typically a connection from the intake air cleaner assembly). On the opposite side of the crankcase, vapors are vented from the crankcase through the valve by way of the outlet hose to the intake manifold. On gasoline engines, the intake manifold provides the vacuum that is needed to accomplish the circulation while the engine is running.

For gasoline engines, the valve is used to regulate the amount of flow based on engine speed. During low engine load operation (e.g., idle), the valve is nearly closed allowing only a small portion of air to flow through the system. With open throttle conditions, the valve opens to allow more air into the system. At high engine load operation (i.e., hard accelerations), the valve begins to close again, limiting air flow to a small amount. For most systems, a mechanical valve is all that is necessary to adequately regulate CV system air flow. The CV system on diesel engines, while slightly different in the typical routing of the hoses and conditions for introducing blow-by gasses into the engine, has essentially the same function.

Problems may occur such that the CV system does not function properly and emissions are vented into the atmosphere. The hoses utilized by the CV system may be subject to cracks or deterioration. However, the staff does not believe that such failures have a significant impact on emissions because vapors are drawn by intake manifold vacuum into the engine. Therefore, air is likely to be drawn into the hose through the crack as opposed to crankcase vapor being forced out. The more likely cause of CV system malfunctions and excess emissions is improper service or tampering of the CV system. These failures include misrouted or disconnected hoses, and missing valves. Of these failures, hose disconnections on the vapor vent side of the systems and/or missing valves can cause emissions to be vented to the atmosphere.

Proposed Monitoring Requirements

Thus, the staff is proposing that manufacturers be required, to the extent feasible, to monitor the CV system for malfunctions. Specifically, staff proposes that manufacturers be required to monitor the CV system for disconnections between the crankcase and the CV valve and between the CV valve and the intake manifold. Because disconnections between the valve and the intake manifold on gasoline engines will result in a significant intake air leak, effective monitoring should be readily achievable through the existing monitoring strategies for the idle air control system or the fuel system. Additionally, if the leak is sufficiently large, the disconnection will render the vehicle inoperable by causing the engine to stall. The staff’s proposal does not require the stored fault code to specifically identify the disconnection if additional hardware would be required for this purpose, and provided service information generated by the manufacturer directs technicians to examine the connection as a possible cause of the indicated fault.

Regarding disconnection between the CV valve and the crankcase on gasoline engines, detection would be significantly more difficult with existing monitors, and would likely require additional hardware such as a pressure switch to ensure flow in the system. However, in order to facilitate cost-effective compliance, the staff proposes to exempt manufacturers from detecting this type of disconnection if certain system design requirements are satisfied. Specifically, for gasoline engines, manufacturers can be exempted from monitoring in this area if the CV valve is fastened directly to the crankcase in a manner that makes technicians more likely to disconnect the intake manifold hose from the valve rather than disconnect the valve itself from the crankcase during service. Staff believes that this would eliminate most of the disconnected hose and valve events because technicians who do not reconnect the intake manifold hose when the service procedure is completed will be alerted to a diagnostic fault as explained in the previous paragraph that will lead the technician back to the disconnected hose.

For gasoline CV system designs that utilize tubing between the crankcase and the valve or any additional tubing or hoses used to equalize pressure or to provide a ventilation path between various areas of the engine (e.g., crankcase and valve cover), the proposed regulation would allow for an exemption from detecting disconnection in this area. This exemption would be obtained if it is demonstrated that all of these connections are resistant to deterioration or accidental disconnection, are significantly more difficult to remove than the connections between the intake manifold and the valve, and are not subject to disconnection during any of the manufacturer's repair procedures for non-CV system repair work. Again, the staff believes these safeguards will eliminate most of the disconnected hose and valve failures previously observed in the field while still providing manufacturers with adequate design flexibility to meet the requirement.

For gasoline engines, the staff is not proposing to require monitoring of the identified CV valve failures that generally do not have a significant impact on emissions such as disconnected fresh air lines and plugged valves. As stated previously, the emission impact is generally minimal (if any effect at all) due to the fact that vapors are not directly vented to the atmosphere. Further, detection of these additional failure modes would almost certainly require additional vehicle hardware. Considering the small emission benefit expected, monitoring would not be cost-effective.

Lastly, manufacturers that utilize CV systems that do not have any external hoses or tubing would be exempted from these monitoring requirements completely. These systems typically use internally machined passageways or other similar arrangements which are not subject to failure modes causing emissions to be vented to the atmosphere.

For vehicles with diesel engines, the staff is proposing that prior to introduction on a production vehicle, manufacturers would be required to submit a plan for Executive Officer approval of the monitoring strategy, malfunction criteria, and monitoring conditions. Executive Officer approval shall be based on the effectiveness of the monitoring strategy to monitor the performance of the CV system to the extent feasible with respect to the proposed malfunction criteria detailed above.

Technical Feasibility of Proposed Monitoring Requirements

The light- and medium-duty OBD II regulations have required identical CV monitoring since the 1996 model year. The technical feasibility has clearly been demonstrated for these packages.

In general, diesel engine manufacturers would be required to meet design requirements for the entire system in lieu of actually monitoring any of the hoses for disconnection. Specifically, the proposed regulation would allow for an exemption for any portion of the system that is resistant to deterioration or accidental disconnection and not subject to disconnection during any of the manufacturer's repair procedures for non-CV system repair work. These safeguards should eliminate most of the disconnected or improperly connected hoses while allowing manufacturers to meet the requirements without adding any additional hardware solely to meet the monitoring requirements.

D. COMPREHENSIVE COMPONENT MONITORING

Background

Similar to the OBD II requirements for light- and medium-duty vehicles, the staff is proposing that manufacturers monitor for malfunctions of comprehensive components on heavy-duty vehicles, which covers all other electronic engine components or systems not mentioned above that either can affect vehicle emissions or are used as part of the OBD diagnostic strategy for another monitored component or system. Comprehensive components are generally identified as input components, which provide input directly or indirectly to the on-board computer, or as output components/systems, which receive commands from the on-board computer. Typical examples of input components include temperature sensors and pressure sensors, while examples of output components/systems include the idle control system, glow plugs, and wait-to-start lamps.

While the emission impact of a malfunctioning comprehensive component may not be as high as the major emission-related components, they still could result in a measurable increase in emissions. With the heavy-duty emission standards becoming increasingly stringent in the near future, manufacturers need to ensure that their emission-control systems are working properly in order to meet these standards. Furthermore, the proper performance of these components can be critical to the monitoring strategies of other components or systems. Malfunctions of comprehensive components that go undetected by the OBD system may disable or adversely affect the robustness of other OBD monitors without any indication. This could potentially result in the failure to detect other faulty emission-related components or systems. Due to the vital role these components play, it is important that they are properly monitored.

A subset of these components that the proposed regulation would require manufacturers to monitor include those that are utilized as part of their heavy-duty idle emission reduction strategies. These strategies would minimize the time spent at idle and require engine manufacturers to forcibly turn off the engine after a specified amount of idle operation, which consequently will lead to less emissions. A malfunction of any of the components used in these strategies may cause the engine to turn off much later than the maximum allowed idle time or not turn off at all, and thus would affect emissions. As such, manufacturers would be required to monitor these components under the comprehensive component requirements.

<u>Proposed Monitoring Requirements</u>

The staff is proposing that manufacturers monitor for malfunctions of comprehensive components. The staff is proposing that input components be monitored continuously for out-of-range and circuit continuity faults (shorts, opens, etc.). Additionally, they would be monitored for rationality faults (e.g., where a sensor reads inappropriately high or low but, unlike out-of-range faults, still within the valid operating range of the sensor) whenever the monitoring conditions are met. Regarding rationality checks, the monitors would be "two-sided" (i.e., detect both inappropriately high and low readings) to the extent feasible and would have reasonable malfunction thresholds and operating conditions (not extreme operating conditions) so that faults are detected efficiently. For example, a reasonable diagnostic for a mass air flow sensor would look for a signal indicating moderate or moderate-to-high engine load, not extremely high engine load (i.e., a near out-of-range value) while the engine is operating at or near idle. Rationality monitoring would be required to use all available information and would generally be accomplished by comparing the output characteristics of multiple sensors that read the same metric during certain engine operating conditions. For example, the output characteristics of the barometric pressure sensor and manifold absolute pressure sensor could be compared during certain conditions to verify either sensor.

The staff is proposing that output components be monitored for proper functional response (i.e., that the component has properly carried out a command from the on-board computer) at least once per driving cycle. If functional monitoring is not feasible, then circuit continuity monitoring would be required. The proposed regulation would contain more specific monitoring requirements for the idle control system, glow plugs, and intake air heater system monitors.

In contrast with other monitors, the proposed regulation would not require illumination of the MIL for all comprehensive component malfunctions. The staff is proposing that a manufacturer illuminate the MIL for comprehensive component failure only if it meets two requirements: (1) a malfunction of the component causes emissions to exceed 15 percent or more of the FTP standard, and (2) the component is used as part of the diagnostic strategy for any other monitored component or system. Even if the MIL is not required to be illuminated, the manufacturer would still be required to store the associated confirmed fault code.

Auxiliary Emission Control Devices

Heavy-duty engine manufacturers are currently allowed to implement auxiliary emission control device (AECD) strategies that activate an alternate engine/fuel/emissions control strategy in order to protect the engine or emission control system. An AECD generally refers to any device or element of design that (1) senses temperature, engine speed, vehicle speed, manifold vacuum, or any other parameter for the purpose of activating, modulating, delaying, or deactivating the operation of the emission control system; and (2) reduces the effectiveness of the emission control system under conditions that may reasonably be expected to be encountered in normal urban vehicle operation and use. Consequently, when an AECD strategy is active, the engine usually emits more emissions into the atmosphere due to the nature of the engine control changes. For the goal of minimizing in-use emissions, it is important to limit manufacturers' use of AECDs to only when they are absolutely necessary. From the perspective of OBD and the more specific goal of minimizing in-use emissions due to emission-related malfunctions, it is important to verify that manufacturers invoke AECDs only when the vehicle is actually operated in conditions that warrant the use of the AECD.

AECDs are usually activated when input parameters reach specific values or other combinations of sensed values meet certain criteria. An overly simplified example is an AECD device that shuts off the exhaust gas recirculation (EGR) system for engine protection if the engine reaches an over-temperature condition. The over-temperature condition may be identified by the engine coolant temperature (or the engine oil temperature) sensor output exceeding a specific temperature. Currently, manufacturers are required to submit their AECD descriptions to ARB for review and approval. When everything is working correctly, most AECDs are generally activated only under “extreme” conditions.

However, when a faulty input component or sensed parameter outputs an incorrect reading, the AECDs can be erroneously activated. For example, if the engine coolant temperature sensor outputs a temperature reading that is much higher than the actual temperature and causes the engine control module to falsely think that the engine is overheating, the AECD will erroneously be activated. The staff is concerned that malfunctions may occur that cause the AECD to activate even during normal driving without any indication to the driver that there is a problem. During such occurrences, vehicle emissions may likely increase substantially.

Accordingly, the staff is proposing that manufacturers be required to monitor any input component, sensed/calculated value, or other parameter that is used to activate an AECD (which, by definition, is emission-related). Specifically, the OBD system would be required to detect a failure of a component, sensed value, or other parameter that would cause the system to falsely activate an AECD. This monitoring requirement would be included as part of the comprehensive component monitoring requirements in the proposed regulation which requires monitoring of any electronic engine component that can affect emissions or is used as part of the monitoring strategy for any other emission-related component. Under the proposed comprehensive component monitoring requirements, manufacturers would be required to monitor input comprehensive components for circuit, out-of-range, and rationality faults. To the extent technically feasible, the staff is expecting manufacturers to design the input comprehensive component rationality monitor to catch the AECD-related faults described above. As described above, a typical rationality monitor uses all available information to identify components that are operating within their normal range but no longer accurate due to sensor drift or deterioration, and are usually “two-sided” (i.e., look for inappropriately high or low readings). The staff wants to ensure that the rationality monitor is able to detect faults at a level that would trigger inappropriate activation of an AECD. Manufacturers would need to either ensure that the “two-sided” rationality monitor is able to detect these faults, add another monitor, or modify their AECD strategy to achieve this.

Additionally, to enable the staff to verify that the monitoring strategies used by the manufacturer cover malfunctions that would falsely trigger AECD activation, manufacturers would be required to submit detailed descriptions of all the AECDs used as part of their OBD certification application (refer to section X of the Staff Report). This description would include the purpose of the AECD, the actions taken when the AECD is activated, and the exact criteria used to decide when the AECD is activated. While this information is currently submitted as part of the engine emission certification application, it is anticipated that manufacturers may follow the path of light-duty manufacturers and submit their OBD certification application for review and approval in advance of the engine emission certification application. As such, the description of the AECDs will need to be included in the OBD application. However, the description required with the OBD application is identical to that required for engine emission certification, so the manufacturer will simply be required to submit the same information at the time of OBD certification (should it occur at a different time than the engine emission certification review).

Technical Feasibility of Proposed Monitoring Requirements

The light- and medium-duty OBD II regulations have required identical comprehensive component monitoring since the 1996 model year. The technical feasibility has clearly been demonstrated for these packages.

E. OTHER EMISSION CONTROL SYSTEM MONITORING

While the heavy-duty OBD regulation would list very specific requirements for most emission controls commonly used today, manufacturers are continually innovating new emission control technologies in addition to refining existing ones. In cases where the technology simply reflects refinements over current technology, the heavy-duty OBD monitoring requirements described above would generally be sufficient to ensure the improved devices are properly monitored. However, in cases where the new technology represents a completely different type of emission control device, the monitoring requirements for existing emission controls may not be easily applied.

Typical devices that fall under this category include hydrocarbon traps and thermal storage devices.

Given that the purpose of OBD is to monitor all emission-related and emission control devices, the staff is proposing to require manufacturers to submit a monitoring plan for ARB's review and approval for any new emission control technology prior to introduction on any future model year vehicles. This policy has worked effectively for the light- and medium-duty OBD II regulation, allowing manufacturers and ARB staff to evaluate the new technology and determine an appropriate level of monitoring that was both feasible and consistent with the monitoring requirements for conventional emission control devices.

Within the proposed requirement, the staff would provide guidance as to what type of components would fall under the requirements of this section instead of under the comprehensive component section. Specifically, staff is concerned that uncertainty may arise for emission control components or systems that also meet the definition of electronic engine components. As such, the proposal would delineate the two by requiring components/systems that fit both definitions but are not corrected or compensated for by the adaptive fuel control system to be monitored as "other emission control devices" rather than as comprehensive components. A typical device that would fall under this category instead of the comprehensive components category because of this delineation is a swirl control valve system. Such delineation is necessary because emission control components generally require more thorough monitoring than comprehensive components to ensure low emission levels throughout a vehicle's life. Further, emission control components that are not compensated for by the fuel control system as they age or deteriorate can have a larger impact on tailpipe emissions relative to comprehensive components that are corrected for by the fuel control system as they deteriorate.

F. EXCEPTIONS TO MONITORING REQUIREMENTS

Under certain conditions, the reliability of certain monitors may be significantly diminished. Accordingly, ARB is proposing to allow manufacturers to disable the affected monitors when these conditions are encountered in-use. These include situations of extreme conditions (e.g., very low ambient temperatures, high altitudes) and of periods where default modes of operation are active (e.g., when a tire pressure problem is detected). In some of these cases, ARB may allow manufacturers to revise the emission malfunction threshold to ensure the most reliable monitoring performance. More details of the exceptions to the proposed monitoring requirements are specified in the proposed regulation.

VII. A STANDARDIZED METHOD TO MEASURE REAL WORLD MONITORING PERFORMANCE

A. Background

In designing an OBD monitor, manufacturers must define enable conditions that bound the vehicle operating conditions where the monitor will execute and make a judgment as to whether a component or system is malfunctioning. Manufacturers would be required to design these enable conditions so that the monitor is: (a) robust (i.e., accurately making pass/fail decisions), (b) running frequently in the real world, and, (c) in general, also running during the FTP heavy-duty transient cycle. If designed incorrectly, these enable conditions may be either too broad and result in inaccurate monitors, or overly restrictive and prevent the monitor from executing frequently in the real world.

Since the primary purpose of an OBD system is to continuously monitor for and detect emission-related malfunctions while the vehicle is operating in the real world, a standardized methodology for quantifying real world performance would be beneficial to both ARB and engine manufacturers. Generally, in determining whether a manufacturer's monitoring conditions are sufficient, a manufacturer would discuss the proposed monitoring conditions with ARB staff. The finalized conditions would be included in the certification applications and submitted to ARB staff, who would review the conditions and make determinations on a case-by-case basis based on the expert judgment of the staff. In cases where the staff is concerned that the documented conditions may not be met during reasonable in-use driving conditions, the staff would most likely ask the manufacturer for data or other engineering analysis used by the manufacturer to determine that the conditions will occur in-use. In proposing a standardized methodology for quantifying real world performance, the staff believes this review process would be made easier and faster. Furthermore, it would better ensure that all manufacturers are held to the same standard for real world performance. Additionally, the staff believes it is necessary to propose procedures that will ensure that monitors operate properly and frequently in the field.

The staff is therefore proposing that all manufacturers be required to use a standardized method for determining real world monitoring performance and hold manufacturers liable if monitoring occurs less frequently than a minimum acceptable level, expressed as minimum acceptable in-use performance ratio. The proposed regulation would require manufacturers to implement software in the on-board computers to track how often several of the major monitors (e.g., catalyst, EGR, PM filter, other diesel aftertreatment devices) execute during real world driving. The on-board computer would keep track of how many times each of these monitors has executed as well as how often the vehicle has been driven. By measuring both these values, the ratio of monitor operation relative to vehicle operation can be calculated to determine monitoring frequency. The proposed requirements would also establish a minimum acceptable monitoring frequency, also expressed as a minimum acceptable in-use performance ratio, that manufacturers must meet for each monitor. The proposal would make it easier for ARB to identify problematic monitors.

The proposed minimum acceptable frequency requirement would apply to many of the OBD system monitors. In the proposed OBD regulation, monitors would be required to operate either continuously (i.e., all the time), “once-per-driving-cycle” (i.e., once per driving event), or in a few cases, "multiple-times-per-driving-cycle" (but only when the proper monitoring conditions are present, not continuously). For components or systems that are more likely to experience intermittent failures or failures that can routinely happen in distinct portions of a vehicle’s operating range (e.g., only at high engine speed and load, only when the engine is cold or hot), monitors would be required to be continuous. Examples of continuous monitors include the fuel system monitor and most electrical/circuit continuity monitors. For components or systems that are less likely to experience intermittent failures or failures that only occur in specific vehicle operating regions or for components or systems where accurate monitoring can only be performed under limited operating conditions, monitors would be required to run “once per driving cycle.” Examples of “once-per-driving-cycle” monitors typically include gasoline catalyst monitors, evaporative system leak detection monitors, and output comprehensive component functional monitors. For components or systems that are routinely used and perform functions that are crucial to maintaining low emissions but may still require monitoring under fairly limited conditions, monitors would be required to run each and every time the manufacturer-defined enable conditions are present. Examples of "multiple-times-per-driving-cycle" monitors typically include input comprehensive component rationality monitors and some diesel exhaust aftertreatment monitors.

Monitors that would be required to run continuously, by definition, would always be running and a minimum frequency requirement is unnecessary. The new frequency requirement would essentially apply only to those monitors that are designated as “once-per-driving-cycle” or "multiple-times-per-driving-cycle." For all of these monitors, manufacturers would be required to define monitoring conditions that ensure adequate frequency in-use. Specifically, the monitors would need to run often enough so the measured monitor frequency on in-use vehicles would exceed the minimum acceptable frequency. However, even though the minimum frequency requirement would apply to nearly all “once-per-driving-cycle” and "multiple-times-per-driving-cycle" monitors, manufacturers would only be required to implement software to track and report the in-use frequency for a few of the major monitors. These few monitors generally represent the most critical emission control components and the most difficult monitors to run. Standardized tracking and reporting of only these monitors should, therefore, provide sufficient indication of monitoring performance.

B. Why frequent monitoring is important

It is important that OBD monitors run frequently to ensure early detection of emission-related malfunctions and, consequently, maintain low emissions. Allowing malfunctions to continue undetected, and thus go without repair, for long periods of time allows emissions to increase unnecessarily. In other words, the sooner the emission-related malfunction is detected and fixed, the fewer the excess emissions that are generated from the vehicle.

Frequent monitoring can also help assure that intermittent emission-related faults (i.e., faults that are not continuously present, but occur for days and even weeks at a time) are detected. The nature of mechanical and electrical systems is that intermittent faults can and do occur, and the less frequent the monitoring, the less likely these faults will be detected and repaired. Additionally, for both intermittent and continuous faults, earlier detection is equivalent to preventative maintenance in that the original malfunction can be detected and repaired prior to it causing subsequent damage to other components. This can help vehicle operators avoid more costly repairs that would have resulted had the first fault gone undetected.

Infrequent monitoring can also have an impact on the service and repair industry. Specifically, monitors that have unreasonable or overly restrictive enable conditions could hinder vehicle repair services. In general, upon completing an OBD-related repair to a vehicle, a technician will attempt to verify that the repair has indeed fixed the problem. Specifically, a technician will ideally operate the vehicle in a manner that will exercise the appropriate OBD monitor and allow the OBD system to confirm that a malfunction is no longer present. This affords a technician the highest level of assurance that the repair was indeed successful.

However, if OBD monitors operate infrequently and are therefore difficult to exercise, technicians may not be able (or may not be likely) to perform such testing. Despite the future proposed ARB service information regulation amendments that would require manufacturers to make all of their service and repair information available to all technicians, including the information necessary to exercise OBD monitors, technicians would still have difficulty in exercising monitors that require infrequently encountered vehicle operating conditions (e.g., abnormally steady constant speed operation for an extended period of time). Furthermore, service information and the time required by the technician to perform this verification would not be free. Ultimately, vehicle owners would pay for this information and labor time through their repair bills. Additionally, in an effort to execute OBD monitors in an expeditious manner or to execute monitors that would require unusual or infrequently encountered conditions, technicians may be required to operate the vehicle in an unsafe manner (e.g., at freeway speeds on residential streets or during heavy traffic). If unsuccessful in executing these monitors, technicians may elect to take shortcuts in attempting to validate the repair while maintaining a reasonable cost for heavy-duty vehicle operators. These shortcuts, however, would likely not be as thorough in verifying repairs and could increase the chance for improperly repaired vehicles being returned to the vehicle owner or additional repairs being performed just to ensure the problem is fixed. In the end, monitors that operate less frequently can result in unnecessary increased costs and inconvenience to both vehicle owners and technicians.

While technicians (and/or heavy-duty vehicle users) may elect not to spend the additional time and money to validate a routine repair, repairs made to pass a heavy-duty inspection test or correct a notice of violation or other citation would require this validation. For an OBD-based inspection, the driver or technician would be required to exercise the OBD monitors and verify that the repairs are successful before the inspection can be performed. This inspection would require specific internal flags in the OBD system known as readiness flags to be set before the vehicle can pass the inspection. These flags would only set upon each of the major OBD monitors executing and completing at least once since the last time fault codes were erased. Vehicles that fail an OBD-based inspection due to the presence of a malfunction would be required to have malfunctions repaired and fault codes cleared before re-testing to verify the repairs. If OBD monitors cannot execute frequently and verify repairs in a timely manner, technicians would have a difficult time preparing a vehicle for re-inspection or would be able to do so only with considerable effort and cost to the heavy-duty vehicle owner. With especially troublesome monitors, heavy-duty vehicle owners may have to wait several weeks or months before the repair is verified, the readiness flag is set by the OBD system, and the vehicle can show proof of correction. In contrast, monitors that function frequently would be easier for technicians and even heavy-duty vehicle owners to exercise. Clearly, monitors that function infrequently would subject heavy-duty vehicle owners to unnecessary delays and/or increased repair costs that would hinder the effectiveness and efficiency of an OBD-based heavy-duty inspection program.

C. Detailed description of software counters to track real world performance

As stated above, manufacturers would be required to track monitor performance by counting the number of monitoring events (i.e., how often each diagnostic has run) and the number of vehicle driving events (i.e., how often has the vehicle been operated). The ratio of the two would give an indication of how often the monitor is operating relative to vehicle operation. Thus:

$$\text{In - Use Performance (Ratio)} = \frac{\text{Number of Monitoring Events (Numerator)}}{\text{Number of Driving Events (Denominator)}}$$

To ensure all manufacturers are tracking performance in the same manner, the proposed regulation would include very detailed requirements for defining and incrementing both the numerator and denominator of this ratio. Manufacturers would be required to have the OBD system keep track of separate numerators and denominators for each of the major monitors, and to ensure that the data are saved every time the vehicle is turned off. The numerators and denominators would be allowed to reset to zero only in extreme circumstances when the non-volatile memory has been cleared (e.g., when the on-board computer has been reprogrammed in the field, when the on-board computer memory has been corrupted). The values could not be reset to zero during normal occurrences such as when fault codes have been cleared or when routine service or maintenance has been performed.

Further, the proposed regulation requires the numerator and denominator to be structured so that the maximum value each can obtain is 65,535 (the maximum number that can be stored in a 2-byte location) to ensure manufacturers allocate sufficient memory space in the on-board computer. If either the numerator or denominator for a particular monitor reaches the maximum value, both values for that particular monitor would be required to be divided by two before counting resumes. In general, the numerator and denominator would only be allowed to increment a maximum of once per driving cycle because most of the major monitors are designed to operate only once per driving cycle. Additionally, incrementing of both the numerator and denominator for a particular monitor would be disabled (i.e., paused but the stored values would not be erased or reset) only when a fault has been detected (i.e., a pending or confirmed code has been stored) that prevents the monitor from executing. Once the fault is no longer detected and the pending fault code is erased, either through the allowable self-clearing process or upon command by a technician via a scan tool, incrementing of both values would be required to resume.

To handle many of these issues, staff has worked with industry and SAE to develop standards for storing and reporting the data to a generic scan tool. This would also help ensure that all manufacturers report the data in an identical manner and thus help facilitate data collection in the field.

1. <u>Number of monitoring events ("numerator")</u>

For the numerator, manufacturers would be required to keep a separate numeric count of how often each of the particular monitors has operated. However, this is not as simple as it may seem. More specifically, manufacturers would have to implement a software counter that increments by one every time the particular monitor meets all of the enable/monitoring conditions for a long enough period of time such that a malfunctioning component would have been detected. For example, if a manufacturer requires a vehicle to be warmed-up and at idle for 20 seconds continuously to detect a malfunctioning catalyst, the catalyst monitor numerator could only be incremented if the vehicle has actually operated in all of those conditions simultaneously. If the vehicle is operated in some but not all of the conditions (e.g., at idle but not warmed-up), the numerator would not be allowed to increment because the monitor would not have been able to detect a malfunctioning catalyst unless all of the conditions were simultaneously satisfied.

Another complication is the difference between a monitor reaching a "pass" or "fail" decision. At first glance, it would appear that a manufacturer should simply increment the numerator anytime the particular monitor reaches a decision, be it "pass" or "fail". However, monitoring strategies may have a different set of criteria that must be met to reach a "pass" decision versus a "fail" decision. As a simple example, a manufacturer may appropriately require only 10 seconds of operation at idle to reach a "pass" decision but require 30 seconds of operation at idle to reach a "fail" decision. Manufacturers would only be allowed to increment the numerator if the vehicle was at idle for 30 seconds even if the monitor actually executed and reached a "pass" decision after 10 seconds. This is necessary because the primary function of OBD systems is to detect malfunctions (i.e., to correctly reach "fail" decisions, not "pass" decisions), and thus, the real world ability of the monitors to detect malfunctions is the parameter that needs to be measured. Therefore, monitors with different criteria to reach a "pass" decision versus a "fail" decision would not be able to increment the numerator solely on the “pass” criteria being satisfied.

It is imperative that manufacturers implement the numerators correctly to ensure a reliable measure for determining real world performance. “Overcounting” would falsely indicate the monitor is executing more often than it really is, while “undercounting” would make it appear as if the monitor is not running as often as it really is. Manufacturers would be required to demonstrate the proper function of the numerator incrementing strategy to ARB prior to certification, and to verify the proper performance during production vehicle evaluation testing.

2. Number of driving events (“denominator”)

The proposed amendments would also require manufacturers to separately track how often the vehicle is operated. In the simplest of terms, the denominator would be a counter that increments by one each time the vehicle is operated. The issue of how to best count or measure vehicle operation was the subject of considerable discussion. Several proposals were considered, including very simple measures such as the number of key starts as well as more complex measures that require several individual criteria to be met on a single driving cycle before it would increment the denominator counter. At this time, the staff is proposing to increment the denominator counter only if several criteria were satisfied on a single driving cycle. This method allows very short trips or trips during extreme conditions such as very cold temperatures or very high altitude to be filtered out and excluded from the count. This is appropriate because these are also conditions where most OBD monitors are neither expected nor required to operate.

Specifically, the denominator would be incremented if on a single key start, the following criteria were satisfied:

(1) minimum engine run time of 10 minutes;
(2) minimum of 5 minutes, cumulatively, of vehicle operation at vehicle speeds greater than 25 miles-per-hour for gasoline engines or calculated load greater than 15 percent for diesel engines; and
(3) at least one continuous idle for a minimum of 30 seconds encountered; and the above three conditions met while:
(4) ambient temperature above 20 degrees Fahrenheit;
(5) altitude of </= 8000 feet.

The staff will work with industry to collect data during the first few years of implementation and make any adjustments, if necessary, to the criteria used to increment the denominator to ensure the ratio provides a meaningful measure of in-use monitoring performance.

D. Proposed standard for the minimum acceptable in-use performance (“ratio”)

Determining how frequent is “frequent enough” for monitors to operate is a complex task that requires consideration of several different factors, including the technical capability of OBD systems, the severity of the malfunction, the consequences of delayed detection and repair of the malfunction, and expected driving patterns and habits. When considering all of these factors, the staff has established a target frequency of malfunction detection (and MIL illumination) within two weeks from occurrence of the fault for 90 percent of the vehicle population. The vast differences in vehicle operation over a two-week period, however, make it difficult to objectively ascertain whether or not this criterion is satisfied. The proposed regulation would attempt to simplify this task by specifying a minimum acceptable monitoring frequency in a quantifiable format, known as the minimum acceptable in-use performance ratio.

In order to determine the appropriate minimum acceptable in-use performance ratio that correlates with the target frequency of two weeks, an analysis of in-use driving patterns of heavy-duty vehicles would need to be conducted. This would take into account the real world variability in driving habits, which would help ensure that the vast majority of heavy-duty vehicles are capable of detecting malfunctions in a timely manner. This analysis requires a fairly large data set of real world driving cycles from all types of vehicles in the heavy-duty industry. While the staff did indeed perform such an analysis for the light-duty OBD II regulation, the staff has not yet identified a suitable database that contains the information necessary to perform such an analysis for the heavy-duty industry. Nevertheless, the staff believes that a minimum ratio must be set to ensure that OBD monitors are indeed running and detecting emission-related malfunctions. Therefore, starting with the 2013 model year, the staff is proposing a minimum ratio of 0.100 for all monitors required to meet the in-use performance requirement. Based on the analysis done during the OBD II regulatory development, a ratio of 0.100 will generally translate to a frequency of malfunction detection within six weeks which is much less frequent than the target of two weeks. However, this ratio will still ensure monitoring is occurring in-use on some portion of the heavy-duty vehicles and will provide manufacturers with considerable flexibility to gain experience during the first few years OBD is required on heavy-duty vehicles. As more data become available, staff will perform a more accurate analysis targeting the two-week standard and modify the proposed minimum acceptable ratio(s) during future rulemaking reviews.

For implementation, the proposal requires manufacturers to implement the software to track and report in-use frequency on one engine family in the 2010 through 2012 model years and on all engine families in the 2013 model year. However, to give manufacturers sufficient time to gain experience with the various drive cycles and habits of heavy-duty applications, the proposal does not require manufacturers to meet a minimum ratio (and thus also includes no in-use liability for enforcement action based on the in-use ratios) for the 2010-2012 model years. For the 2013-2015 model years, all engines will be required to meet the minimum ratio of 0.100, however, in-use liability will be limited. Specifically, liability for enforcement action will be limited to monitors that fall below a ratio of 0.05 (which represents a frequency of MIL detection in 12 weeks or twice as long as the required minimum ratio). For 2016 and subsequent model years, all engine families would be liable for in-use enforcement action if they fail to meet the minimum ratio of 0.100.

VIII. STANDARDIZATION REQUIREMENTS

Starting with the 2013 model year, the heavy-duty OBD regulation would include requirements for manufacturers to standardize certain features of the OBD system. Effective standardization assists all repair technicians in diagnosing and repairing malfunctions by providing equal access to essential repair information, and requires structuring the information in a common format from manufacturer to manufacturer. Additionally, the standardization would help facilitate the potential incorporation of OBD checks into the existing heavy-duty inspection programs.

Among the features that would be standardized under the proposed heavy-duty OBD regulation include the diagnostic connector, communication protocol, hardware and software specifications for tools used by service technicians, the information made available by the on-board computer, the methods for accessing the information, the numeric fault codes stored when a malfunction is detected, and the terminology used by the manufacturer in service manuals.

One important aspect to keep in mind is that the proposal by staff would only require that a certain minimum set of emission-related information be made available through the standardized format, protocol, and connector selected by staff. It does not limit engine or vehicle manufacturers as to what protocol they use for engine or vehicle control, communication between on-board computers, or communication to manufacturer-specific scan tools or test equipment. Further, it does not prohibit engine or vehicle manufacturers from equipping the vehicle with additional diagnostic connectors or protocols as required by other suppliers or purchasers. For example, fleets that use data logging or other equipment that requires the use of SAE J1587 communication and connectors could still be installed and supported by the engine and vehicle manufacturers. The OBD rules would only require that manufacturers also equip their vehicles with a specific connector and communication protocol that meet the standardized requirements to communicate a minimum set of emission-related inspection and diagnostic information.

The standardization requirements will not be required until 2013. While the staff's proposal requires the phase-in of OBD systems on one engine family for the 2010 through 2012 model years, all other engines sold in that timeframe will essentially continue to meet the requirements of EMD. Because EMD does not require any standardization, truck and coach builders could be faced with several integration issues when building product in 2010 through 2012. Specifically, they would be faced with items like accommodating a standardized MIL, diagnostic connector, and communication protocol on some engines while having completely different systems on other engines. Rather than force truck and coach builders to try and handle two different systems and risk incompatibilities, the proposed regulation exempts all 2010 through 2012 model year engines from meeting the standardization requirements of OBD. This will allow truck and coach builders to integrate engines in the same manner as currently done and then to switch over to integrating a single system in 2013 when all engines are required to meet OBD.

A. Communication Protocol

During the initial years of implementation of the light- and medium-duty OBD II regulation, ARB allowed manufacturers to use one of four protocols for communication between a generic scan tool and the vehicle's on-board computer. A generic scan tool would automatically cycle through each of the allowable protocols to establish communication with the on-board computer. While this has generally worked successfully in the field, some communication problems have arisen in the field due, in part, to the use of multiple protocols. Recent amendments to the OBD II regulation now require all manufacturers to use only one protocol by the 2008 model year to help address this issue.

Thus, from staff's experience with standardization under the OBD II regulation, it is desirable to have a single set of standards used by all heavy-duty vehicles. Staff has found this is generally beneficial for the service and repair industry, inspections, diagnostic equipment and tool manufacturers, and the regulatory agencies in terms of verifying all vehicles are built in conformance with the standards. A single protocol also offers a tremendous benefit to scan tool designers as well as technicians. Scan tool designers can focus on added feature content and can expend much less time and money validating basic functionality of their product on all the various permutations of protocol interpretations that are implemented. As such, technicians will likely get a scan tool that works properly on all vehicles without the need for repeated software updates that incorporate "work-arounds" or other patches to fix bugs or adapt the tool to accommodate slight variances in how the multiple protocols interact with each other or are implemented by various manufacturers. Further, a single protocol is also beneficial for fleet operators that utilize add-on equipment such as data loggers and for vehicle manufacturers that integrate various engine and component suppliers that eventually must all work together. Thus, it was initially staff's goal to end up with a single set of standards for all heavy-duty vehicles.

The heavy-duty industry, however, has been divided over which single protocol to use and has strongly argued for more than one protocol to be allowed. Thus, for vehicles with diesel engines, the staff is proposing to require manufacturers to conform to either one of the following two sets of standards: SAE 1939 or ISO 15765 (500 kbps baud rate version). For vehicles with gasoline engines, the staff is proposing to require manufacturers to only use ISO 15765 (500kbps baud rate version). Manufacturers would be required to use only one standard to meet all the standardization requirements on a single vehicle; that is, a vehicle must use only one protocol for all OBD modules on the vehicle.

Several in the heavy-duty industry have also argued for more than these two protocols as options for heavy-duty engines. Others have even argued for combinations of these protocols (e.g., diagnostic connector and messages of ISO 15765 on an SAE J1939 physical layer network). However, as described above, staff's experience from multiple protocols and multiple variants within the protocols has unnecessarily caused a significant number of problems with proper communication. Further, equipment and tool manufacturers (e.g., scan tool manufacturers) have also expressed a concern regarding proliferation of multiple variants and have generally indicated support for a single protocol. Lastly, during discussions with staff members for various state I/M programs (outside of California), repeated requests have been made to limit the communication protocol options to avoid the problems they have faced in updating and modifying their test equipment to communicate with every variant of protocols that were allowed on light-duty vehicles.

As stated above, heavy-duty vehicles with gasoline and diesel engines would be allowed to use ISO 15765 (500 kbps baud rate version) as the communication protocol. This is the same standard starting to be used in the light-duty industry in the 2003 model year and required on all light- and medium-duty vehicles by the 2008 model year. By harmonizing with the light-duty protocol, equipment and tool manufacturers will be able to adapt existing tools very easily to work on heavy-duty vehicles and will provide even more diagnostic equipment choices for heavy-duty repair and maintenance personnel. Further, the ISO 15765 and associated ISO 15031 standards have already been updated to accommodate nearly every standardized requirement proposed for heavy-duty vehicles. The use of the 15765 protocol and 15031 messages will also provide a consistent format for technicians and inspectors on all types of vehicles. Lastly, the use of the same protocol used in current medium-duty applications provides vehicle and engine manufacturers (as well as other suppliers) that currently produce product for both the medium-duty and the heavy-duty sectors the ability to use a common software set for all products.

As stated above, the proposed regulation would allow heavy-duty vehicles with diesel engines to use SAE J1939. There are some distinct advantages that SAE J1939 could have over the ISO 15765 protocol. One such advantage could be the opportunity to access not only the minimum parameter set required by the OBD regulation but to access all parameters available on the vehicle through the same protocol and message structure. This would be a clear advantage for repair technicians by providing a more powerful repair tool if all of these additional parameters are standardized and can be automatically translated by the scan tool without any additional manufacturer-specific software. In the same manner, SAE J1939 could offer the ability to access enhanced emission-related (and potentially non-emission-related) diagnostic information other than just parameters with a single tool and without manufacturer-specific software/cartridges/adapters to translate the information. However, discussions with some in the heavy-duty industry have indicated that the majority of "enhanced" (e.g., beyond the minimum required by the OBD regulation) diagnostic information, while accessed through the J1939 connector on the J1939 network, is not accessed using defined and standardized J1939 messages (nor is it required to be by SAE J1939) in a manner that would automatically translate the results to useable information for a repair technician. As such, manufacturer-specific scan tool software is still required to access and use the enhanced information for a particular engine model and make. If this is the case, then SAE J1939 offers little advantage in this aspect relative to the ISO 15765 protocol as repair technicians would still be required to purchase additional scan tool software every year for each specific make and model.

B. Diagnostic Connector

All vehicles would be required to incorporate a diagnostic connector conforming to the specifications contained in the standards ultimately selected. The diagnostic connector would be required to be located in the driver’s side foot-well region of the vehicle interior and would need to be easily identified and reachable by a technician or inspector crouched or standing on the ground on the driver's side of the vehicle with the vehicle driver's door open. Additionally, if a manufacturer wished to utilize a cover over the connector, the manufacturer would be required to label the cover with the text "OBD" to assist technicians in identifying its location and would be required to make the cover easily removable by hand (without the use of tools). The manufacturer would be required to submit the label to ARB for approval. The staff's experience from the light-duty industry has been that connectors that are difficult to locate cause unnecessary but substantial problems both in the repair community and the I/M community. Further, feedback from ARB heavy-duty inspectors has indicated that a location that would be easily accessible without entering the vehicle and while standing on the ground provides the most efficient means for inspection and would be preferred by most vehicle owner/operators.

C. Readiness Status

Manufacturers would be required to incorporate readiness status indications of several major emission control systems and components into their vehicles, which would determine if the OBD monitors have performed their system evaluations. When the vehicle is scanned, the monitor would report a readiness status of either “complete” (if the monitor has run a sufficient number of times to detect a malfunction since the memory was last cleared), “incomplete” (if the monitor has not yet had the chance to run since the memory was last cleared), or “not applicable” (if the monitored component in question is not equipped or monitored on the vehicle). The readiness status of monitors that are required to run continuously would always indicate “complete.” The proposed heavy-duty OBD regulation details the process of setting readiness status for each monitor. The readiness status would be set to “incomplete” whenever the fault memory is cleared either by a battery disconnect or by a scan tool, but not after a normal vehicle shutdown (i.e., key-off).

The main intent of the readiness status is to ensure a vehicle is ready for an OBD-based inspection (i.e., that monitors have run) and to prevent fraudulent testing. In general, for OBD-based inspections, technicians “fail” a vehicle if the MIL is illuminated, which indicates a fault is currently present. Without readiness status, drivers (or even technicians) could possibly avoid “fail” designations by disconnecting the battery and clearing the computer memory prior to an inspection, which erases any pre-existing fault codes and extinguishes the MIL. The readiness status information allows a technician or inspector to determine if the memory in the on-board computer has been recently cleared (e.g., by a technician clearing fault codes or disconnecting the battery). With the potential incorporation of OBD checks into the existing heavy-duty inspection programs in the future, the staff anticipates that the readiness status would be used in this manner.

Technicians could also potentially use the readiness status to verify OBD-related repairs. Specifically, technicians would clear the computer memory after repairing an OBD-detected fault in order to erase the fault code, extinguish the MIL, and reset the readiness status to "incomplete." Then the vehicle could be operated in such a manner that the monitor of the repaired component would be exercised (i.e., the readiness status of the monitor is set to "complete"). The absence of any fault codes or MIL illumination would indicate a successful repair.

Unfortunately, the presence of unset readiness flags may be due to circumstances beyond the driver's control (i.e., the vehicle was not driven under the conditions necessary to run some of the monitors) and these drivers would be rejected during inspection testing. For example, vehicle operation solely in extreme ambient conditions would prohibit monitors from running and setting readiness status to "complete".[21] As another example, if a vehicle with the MIL illuminated was repaired shortly before an inspection, there may be instances where the vehicle has not had sufficient time to operate (i.e., exercise the monitors) after the repair services so that it may have unset readiness flags. These vehicles may consequently be rejected or failed in an inspection.

Originally, ARB staff envisioned that all readiness flags on a vehicle would be required to be set to "complete" prior to inspection testing. Given the situations cited above and trying to balance vehicle operator inconvenience with fraud detection, the U.S. EPA recommends allowing vehicles to pass the light- and medium-duty OBD-based inspection as long as there are two or fewer readiness flags set to "incomplete" (most vehicles have a total of four readiness flags). However, a substantial amount of feedback regarding readiness flags and clearing of codes prior to inspection has been gathered in the last few years as 17 states across the nation, including California, have implemented some form of OBD II inspection into the I/M program. Specifically, there is now more evidence that the "two or fewer" criterion that knowingly created a potential loophole for vehicles to fraudulently get through an I/M inspection is indeed being exploited by vehicle owners, technicians, and inspectors. As such, the proposal for heavy-duty OBD includes additional improvements to the readiness flag logic that will better differentiate between vehicles that are attempting to fraudulently get through an OBD-based inspection prior to re-detection of a fault and those that have been correctly repaired recently or otherwise have unset readiness flags through no fault of the vehicle operator.

[21] To address the issue of extreme ambient conditions, the proposed regulation would allow, subject to Executive Officer approval, that in situations where monitors have been disabled for multiple driving cycles due to extreme ambient conditions, the readiness status for the subject monitors would be set to "complete," even if monitoring has not been completed.

Distance and Number of Warm-up Cycles Since Code Clear

The staff's proposal would require all vehicles to make available data on the distance elapsed (or engine run time for engines that do not utilize vehicle speed information) and the number of warm-up cycles since the fault memory was last cleared. By combining these data with the readiness data, technicians or inspectors would better be able to determine if unset readiness flags or an extinguished MIL are due to recent clearing of the memory or circumstances beyond the driver’s control. For example, a vehicle with several "incomplete" readiness flags but with a high number of miles traveled (or engine run time) and of warm-up cycles since code clear would be less likely to have undergone a recent clearing event solely to extinguish the MIL prior to inspection. On the other hand, a vehicle even with only one or two "incomplete" readiness codes and a very low number of miles traveled (or engine run time) and warm-up cycles since code clear would be a more likely candidate to be rejected or failed at an inspection. This would better allow an inspection program to be set up to reject only those vehicles with recently cleared memories while minimizing the chance to reject vehicles that have monitors that are difficult to execute or possess monitoring conditions that are not frequently encountered due to the specific vehicle owner's driving habits.

Permanent Diagnostic Trouble Code Storage

The staff is also proposing a requirement to make it much more difficult for a vehicle owner or technician to clear the fault memory and erase all traces of a previously detected fault. Currently for light- and medium-duty vehicles, a technician or vehicle owner can erase all fault codes and extinguish the MIL by issuing a command from a generic scan tool plugged into the vehicle or, in many cases, simply by disconnecting the vehicle battery. While this does reset the readiness status for all monitors to "incomplete" and would reset the two counters described in the previous paragraph to zero, it also removes all trace of the previous fault that was detected on the vehicle.

The staff's proposal would require manufacturers to be able to store a minimum of four confirmed or active fault codes that are presently commanding the MIL on in non-volatile memory (NVRAM) at the end of every key cycle. By requiring these permanent fault codes to be stored in NVRAM, vehicle owners would not be able to erase them simply by disconnecting the battery. Further, manufacturers would not be allowed to clear or erase these "permanent" fault codes by any generic or manufacturer-specific scan tool command. Instead, these fault codes would only be allowed to be self-cleared by the OBD system itself, once the monitor responsible for setting that fault code has indeed run and passed enough times that is has confirmed that the fault is no longer present. Once this has occurred, the specific fault code stored in NVRAM would be erased. Thus, if more than one emission-related fault existed, to erase all the permanent fault codes stored in NVRAM, each monitor related to each permanent fault code would have to run and pass.

This approach provides several benefits to an inspection program. First, it would allow a program to very specifically target and reject/fail only those vehicles that have recently had the MIL illuminated and have not subsequently been driven enough to exercise the specific monitor previously responsible for illuminating the MIL on that vehicle. With readiness status, programs are forced to either require that all monitors have run and passed since the last code clear or allow some monitors to remain incomplete and gamble that the incomplete monitors are not the ones that were previously responsible for illuminating the MIL on that particular vehicle. For example, a vehicle could show up at an inspection with the catalyst monitor incomplete and the EGR monitor complete. If that particular vehicle recently had a MIL on for a catalyst fault, it could still have the fault present and ideally, it would fail until the catalyst monitor was complete. However, if that particular vehicle recently had a MIL on for an EGR fault, it is highly likely that the EGR fault has been confirmed to no longer be present because the readiness status for EGR is complete and there is less likelihood that the vehicle is sneaking through the inspection with a fault still present, even though the catalyst monitor is still incomplete. Unfortunately, with only the readiness status to make a decision on, there is no way for a technician or inspector to know which of the above two cases applies to the vehicle. With the permanent fault code method, however, an inspection program could better pinpoint and reject/fail only those vehicles that indeed have recently had the MIL on and have not had an opportunity to re-run that same monitor. For the first case in the above example, a permanent fault code for the catalyst would be present if the vehicle indeed had recently had a catalyst MIL-on fault and had not yet had a chance to re-run the monitor. The lack of a permanent fault code for the catalyst would provide a high degree of confidence that the vehicle does not need to be failed because, even though the catalyst monitor has not run since code clear to reset the readiness status, this particular vehicle has not recently had the MIL on for a catalyst fault. In this manner, inspection programs could reject/fail any vehicle that has a permanent fault code stored in it while it could potentially pass any vehicle that had zero permanent fault codes stored in it.[22]

The permanent fault code method also has advantages for a technician attempting to repair a vehicle and then prepare it for inspection or proof of correction. The permanent fault code would identify the specific diagnostic that would need to be exercised after repair and prior to inspection to remove the permanent fault code. By combining this information with the vehicle manufacturer's service information, technicians could identify the exact conditions necessary to operate a particular monitor. As such, technicians could more effectively target after repair verification and would be able to verify that the specific monitor that previously illuminated the MIL has run and confirmed the repair has been made correctly. This also provides added incentive for the

[22] An OBD based inspection program would likely still want to require some or all of the readiness flags to be complete at the time of inspection instead of relying solely on the presence of permanent fault codes. This is due to the structure of most OBD systems, which may disable relevant monitors upon detection of a fault with one or more related components. If the vehicle owner ignored the detected fault for a substantial period of time, other components could have subsequently malfunctioned but will not be monitored until the first malfunction has been repaired. Requiring some or all readiness complete will increase the likelihood that the vehicle is not in a condition to trigger a "chain" of successive faults.

technician to "fix it right the first time" and reduces vehicle owner "come-backs" for incomplete or ineffective repairs.

Real Time Indication of Monitor Status

Provisions are also proposed to make it easier for technicians to prepare the vehicle for an inspection following a repair by providing real time data which indicates whether certain conditions necessary to set all the readiness flags to "complete" are currently present. These data would indicate whether a particular monitor still has an opportunity to run on this driving cycle or whether a condition has been encountered that has disabled the monitor for the rest of the driving cycle. While these data would not provide technicians with the exact conditions necessary to exercise the monitors (only service information will do that), this information in combination with the service information should facilitate technicians in verifying repairs and/or preparing a vehicle for inspection. Technicians would be able to use this information to identify when specific monitors have indeed completed or to identify situations where they have overlooked one or more of the enable criteria and need to check the service information and try again.

Communicating Readiness Status to Vehicle Operator

As mentioned above, substantial feedback has been received through the roll-out of OBD II-I/M programs throughout the U.S. and much of this feedback has to do with the issues regarding the effect on vehicle owners because of possible rejection from I/M testing due to unset readiness flags. To address this, some light-duty manufacturers requested the option to communicate the vehicle’s readiness status directly to the vehicle owner without the use of a scan tool. This would allow the vehicle owner to be sure that the vehicle is ready for inspection prior to taking the vehicle to an I/M station. Such a provision was recently adopted in the OBD II regulation. The staff is also proposing to allow heavy-duty manufacturers to do the same. If manufacturers choose to implement this option, though, they would be required to do so in the standardized manner prescribed in the proposed regulation. On vehicles equipped with this option, the vehicle owner would be able to initiate a self-check of the readiness status, thereby knowing ahead of time whether the vehicle would likely pass a re-inspection (e.g., to show proof of correction after failing a previous roadside inspection).

D. Fault Codes

Fault codes are the means by which malfunctions are reported by the OBD system and displayed on a scan tool for service technicians. The proposed heavy-duty OBD regulation would require manufacturers to report all emission-related fault codes using a standardized format and to make them accessible to all service technicians, including the independent service industry. The standards selected would define many generic fault codes to be used by all manufacturers. In the rare circumstances that a manufacturer cannot find a suitable fault code already standardized, a unique “manufacturer-specific” fault code could be used. However, these manufacturer-specific codes are not as easily interpreted by the independent service industry. Increased usage of manufacturer-specific codes may increase the time and cost for vehicle repairs. Thus, the proposed regulation would restrict the use of manufacturer-specific fault codes. If a generic fault code suitable for a given malfunction cannot be found, the regulation would require the manufacturer to pursue approval of additional generic fault codes to be added. This proposal would affirm the intent of the OBD regulation to standardize as much information as possible.

Additionally, the staff is proposing that the OBD system store fault codes that are as specific as possible to identify the nature of the fault, which would provide technicians with detailed information necessary to diagnose and repair vehicles in an efficient manner. In other words, manufacturers should use separate fault codes for every diagnostic where the diagnostic and repair procedure or likely cause of the failure is different. Generally, a manufacturer would design an OBD monitor that detects different root causes (e.g., sensor shorted to ground or battery) for a malfunctioning component or systems. The staff expects manufacturers to store a specific fault code such as “sensor circuit high input” or “sensor circuit low input” rather than a general code such as “sensor circuit malfunction.” The staff further expects manufacturers to store different fault codes distinguishing circuit faults from rationality and functional checks, since the root cause for each problem is different, and thus the repair procedures may be different.

For most OBD strategies, manufacturers would be expected to illuminate the MIL only after the same malfunction has occurred on two separate driving events. This “double” detection would ensure that a malfunction truly exists before alerting the vehicle operator. The first time a malfunction is detected, a “pending” fault code identifying the suspected failing component or system would be stored in the on-board computer. If the same malfunction is again detected the next time the vehicle is operated, the MIL would be illuminated and a “confirmed” or “active” fault code would be stored. A technician would use the “confirmed” or “active” fault code to determine what system or component has failed. A “pending” fault code, however, could be used by service technicians to help diagnose intermittent problems as well as to verify that repairs were successful. In these instances, a technician could use the “pending” fault code as a quicker, earlier warning of a suspected (but as yet unconfirmed) problem. The staff is proposing that manufacturers store and make available a “pending” fault code for each currently malfunctioning monitored component or system, regardless of the MIL status or the presence of a “confirmed” or “active” fault code. Descriptions of the proposed fault code storage and erasure requirements are described in section III. B. of the Staff Report.

The staff is also proposing requirements that would help distinguish between fault codes stored for present faults and fault codes stored for past faults on engines using ISO 15765-4 as the communication protocol. As described in section III. B., a manufacturer would generally be allowed to extinguish the MIL if the malfunction responsible for the MIL illumination is not detected (i.e., the monitor runs and determines that the fault no longer exists) on three subsequent sequential driving cycles. However, a manufacturer would not be allowed to erase a confirmed fault code unless the identified malfunction associated with the code is not detected in at least 40 engine warm-up cycles and the MIL is not presently illuminated for the malfunction. So even though the malfunction may no longer be present and the MIL not illuminated, the fault code would still remain as a “history” code. Consequently, if another unrelated fault occurs and the MIL illuminates for this new fault, another fault code would be stored in addition to the “history” code. When trying to diagnose the OBD problem, technicians accessing fault code information may have trouble distinguishing which fault code is responsible for illuminating the MIL (i.e., which fault actually exists), and thus would have problems determining what exactly must be repaired. Therefore, the staff is proposing requirements that would help distinguish a fault code that illuminates the MIL and a “history” code. For engines using SAE J1939 as the communication protocol, such a distinction is already available and defined as pending codes, active codes, and previously active codes.

"Permanent" fault codes (described above in section VIII. C.) would also need to be separately identified from the other types of fault codes. The staff is also working with the standards setting committees to best determine the method for doing this, but it will likely be done in a similar manner to that used to distinguish the other types of codes. Additionally, as mentioned above, manufacturers would be required to develop additional software routines to properly store and erase permanent fault codes in NVRAM and prevent erasure from any battery disconnect or scan tool command.

E. Data Stream/Freeze Frame/Test Results

An important aspect of OBD is the ability of technicians to access critical information from the on-board computer in order to diagnose and repair emission-related malfunctions. ARB believes there are certain emission critical components and systems for which electronic information access through the data link connection would provide invaluable assistance in properly repairing vehicles. The availability of real-time information would also greatly assist technicians in responding to driveability complaints because the vehicle could be operated under the problem conditions and the technician would be able to know how various sensors and systems were acting at that time. Fuel economy complaints, loss of performance complaints, intermittent problems, and others could also be addressed.

The proposed regulation defines a number of data parameters that manufacturers would be required to report to generic scan tools. These parameters, which would include information such as engine speed and exhaust gas sensor readings, would allow technicians to understand how the vehicle engine control system is functioning, either as the vehicle operates in a service bay or during actual driving. They would also help technicians diagnose and repair emission-related malfunctions by allowing them to watch instantaneous changes in the values while operating the vehicle.

Some of the data parameters proposed are also intended to assist ARB and U.S. EPA staff in performing testing of the engines including testing for compliance with the emission standards themselves. One of these parameters that manufacturers would be required to report is the real-time status of the NOx and PM “not-to-exceed” (NTE) control areas. The NTE standards define a wide range of engine operating points where a manufacturer must design the engine to be below a maximum emission level. In theory, whenever the engine is operated within the speed and load region defined as the NTE zone, emissions will be below the required standards. However, within the NTE zone, manufacturers are allowed, on a case-by-case basis, to be exempted from the emission standards within specific regions. Manufacturers can request and be approved for both 5 percent carve-out regions (limited test regions where no more than 5 percent of in-use operation is expected and thus, no more than 5 percent of emission sampling can be collected) and for NTE deficiencies (defined exemption areas where manufacturers are not required to meet the emission standards). These regions can be defined by directly measured signals, or more often, by complicated modeled values calculated internally in the engine computer. When conducting emission testing of these engines, it is imperative to know if the engine is in the NTE region (and thus, subject to the standards) or outside of the region or in a NTE deficiency region (and thus, not subject to the standards), or in a 5 percent carve-out region (and thus, subject to only limited testing in that region). Without this parameter, emission testing by ARB and U.S. EPA would be significantly more difficult to accomplish (e.g., by requiring off-board duplication of the internal engine computer’s proprietary algorithms, models, and calculations to try and determine if any of the 5 percent carve-out or NTE deficiency conditions are presently active).

In the event an emission-related malfunction is detected by the OBD system, the proposed regulation would also require manufacturers to make available “freeze frame” information, which displays the operating conditions of the vehicle at the time of malfunction detection, in addition to the fault code associated with the data. The required freeze frame data would include the calculated load value, engine speed, and engine coolant temperature. Further, the required freeze frame data would be required to include all other standardized data parameters available in the on-board computer that detected and stored the fault. For the purposes of this requirement, "available" means any other data parameter that is input to (directly wired or sent via other modules or network messages) or calculated within the on-board computer. This would allow the freeze frame data to assist the technician in two ways. First, the technician should be able to identify how the vehicle was being operated by the driver at the time of the fault should he or she need to duplicate the driving conditions to find an intermittent malfunction or verify a repair under the same conditions where it was originally detected. Second, the inclusion of all other available data provides the technician with the ability to "see" some of what the on-board computer was seeing when it set the malfunction. This can be particularly useful when a specific fault is indeterminate (e.g., could have been caused by more than one root cause or more than one malfunctioning sensor).

The proposed regulation would also require manufacturers to store the most recent monitoring results for most of the major monitors. Manufacturers would be required to store and make available to the scan tool certain test information (i.e., the minimum and maximum values test limits as well as the actual test value) of the most recent monitoring event. “Passing” systems would store test results that are within the test limits, while “failing” systems would store results that are outside the test limits. The storage of test results would greatly assist technicians in diagnosing and repairing malfunctions and would help distinguish between components that are performing well below the malfunction thresholds from those that are potentially marginally passing the malfunction thresholds.

F. Identification Numbers (Cal ID, VIN, CVN)

The staff is also proposing that manufacturers be required to report two identification numbers related to the software and specific calibration values in the on-board computer. The first item, Calibration Identification Number (CAL ID), would identify the version of software installed in the vehicle. Subsequent releases of software by the manufacturer that make changes to the emission controls or OBD system would require a new CAL ID. The second item, Calibration Verification Number (CVN), would help ensure that the software has not been inappropriately corrupted, modified, or tampered with. Both CAL ID and CVN help ensure the integrity of the OBD II system. CVN would require manufacturers to develop sophisticated software algorithms that can verify the integrity of the emission-related software and ensure that the diagnostic routines and calibration values have not been corrupted or modified inappropriately. The CVN would essentially be a self-check calculation of all of the emission-related software and calibration values in the on-board computer and would return the result of the calculation to a scan tool. If the calculated result did not equal the expected result for that CAL ID, the software would be known to be corrupted or otherwise modified. The proposed regulation would require that the CVN result be made available at all times to a generic scan tool.

The proposed regulation would also require manufacturers to make available an additional identification number, the Vehicle Identification Number (VIN), in a standardized format. The VIN would be a unique number assigned by the vehicle manufacturer to every vehicle built. The VIN is commonly used for purposes of ownership and registration to uniquely identify every vehicle. For the heavy-duty industry, the VIN is used to identify the vehicle on citations or notice-of-violations (NOVs) issued at roadside inspections under the HDVIP. By requiring the VIN to be stored in the vehicle and available electronically to a generic scan tool, the possibility of a technician or inspector performing a fraudulent inspection (e.g., by plugging into a different vehicle than the citation or NOV was issued for to generate a proof of correction) would be minimized. Electronic access to this number would also greatly simplify the inspection process and reduce transcription errors from manual entry.

The proposed heavy-duty OBD regulation would require the VIN to be electronically stored in a control module, not necessarily the engine control module, in the vehicle. As long as the VIN is correctly reported according to the standards selected, it is irrelevant as to which vehicle module (e.g., engine controller, instrument cluster controller) contains the information. And, while the ultimate responsibility would lie with the engine manufacturer to ensure that every vehicle manufactured with one of its engines satisfied this requirement by having the VIN available, the physical task of implementing this requirement would likely be passed from the engine manufacturer to the vehicle manufacturer via an additional build specification. Thus, analogous to how the engine manufacturer currently provides engine purchasers with detailed specifications regarding engine cooling requirements, additional sensor inputs, physical mounting specifications, weight limitations, etc., the engine manufacturer would likely include an additional specification dictating the need for the VIN to be made available electronically. It would be left to each engine manufacturer to determine the most effective method to achieve this, as long as the VIN requirement is met. Some manufacturers may find it most effective to provide the capability in the engine control module delivered with the engine coupled with a mechanism for the vehicle manufacturer to program the module with the VIN upon installation of the engine into an actual vehicle. Others may find it more effective to require the vehicle manufacturer to have the capability built into other modules installed on the vehicle such as instrument cluster modules, etc. It should also be noted that staff has observed several current vehicles with engines from three different engine manufacturers that already have the vehicle VIN available through engine-manufacturer specific scan tools indicating that such arrangements already exist in one form or another.

G. Tracking Requirements

In-use Performance Ratio Tracking Requirements

The tracking requirements for the in-use performance ratios are discussed in section VII of the Staff Report and listed in the proposed regulation.

Engine Run Time Tracking Requirements

The staff is proposing a requirement for manufacturers to log engine operating time spent in various operating conditions. Specifically, manufacturers would be required to log basic engine operating data including cumulative engine on run time, cumulative engine on idle time, and cumulative engine run time with a power take-off (PTO) unit active.. The proposed regulation would set a minimum resolution for each of these counters and require all these counters to be stored in non-volatile memory (NVRAM) so that vehicle owners or operators would not be able to erase them simply by disconnecting the battery nor would the values be able to be erased via a scan tool command.

Regarding the logging of idle operation, in some truck applications such as long-haulers with sleeper cabs, considerable time can be spent operating at idle. By requiring manufacturers to implement a separate counter identifying "engine operating at idle," the staff would be better able to separate out engine run time at idle from non-idle. Further, as stated previously in section VI.D. of the Staff Report, ARB is proposing under a separate rulemaking, idle-off requirements to minimize time spent at idle and to require engine manufacturers to implement strategies that forcibly turn off the engine after a specified amount of idle operation. By logging idle operation, staff would be able to better quantify how well such strategies are working. Future heavy-duty inspections could also potentially use this parameter to help identify vehicles that warrant further testing and/or inspection to see if they have been tampered or otherwise modified to bypass the idle-off strategies.

Additionally, a large segment of the heavy-duty applications use PTO units which use the powertrain to drive auxiliary equipment such as cherry pickers, cement mixers, trash compactors, etc. In some applications, the PTO device is activated infrequently or only while the vehicle is stopped while in other applications, the PTO device may be activated near continuously. To limit the scope of development work engine manufacturers are required to do when validating monitors, the proposed OBD regulations allow manufacturers to disable affected monitors when the PTO device is activated. However, given the range of PTO devices and usage patterns, it is relatively unknown what impact this has on in-use monitoring frequency. As such, manufacturers who utilize the provision to disable one or more OBD monitors during PTO device activation would also be required to log engine run time while a PTO device is active. This would provide an indication of what percentage of engine operating time is spent with monitors disabled and could be used to determine if the policy of allowing monitor disablement during PTO device activation needs to be revisited or modified in the future. The staff would also be better able to interpret in-use monitoring frequency data (as detailed in section VII. of the Staff Report). Specifically, for monitors that seem to demonstrate very low monitoring frequency, the staff could determine if this was due to frequent PTO activation (if the PTO active counter was really high) or due to other conditions.

H. Service Information

Once a malfunction has been detected by the OBD system, the emission reduction benefits are obtained only when the problem is corrected. When repairing an OBD-related problem, a repair technician generally accesses the available information from the on-board computer to determine the component or system that failed. After repairing the malfunction, the vehicle would then be driven in a manner such that the monitor for the malfunctioning component runs and determines that the fault no longer exists. In order to do this, the repair technician would need information that would help pinpoint the malfunctioning component, determine the cause of the malfunction, and ensure that the problem has indeed been corrected. Therefore, access to adequate service information is an important part of the OBD program. Specifically, all emission-related vehicle service information necessary to make use of the OBD system and to perform emission-related repairs should be made available to all service technicians, including independent and aftermarket service technicians, and in a format for easy accessibility of the information.

For the light- and medium-duty vehicles, the service information requirements are detailed in a stand-alone regulation, section 1969 of title 13, California Code of

Regulations, which requires this information to be made available on the internet. The required information includes OBD monitor descriptions, information necessary to execute each monitor (e.g., enable conditions), information on how to interpret the test data accessed from the on-board computer, and other information. ARB is currently revising section 1969 to include service information requirements for heavy-duty vehicles.

However, in the unlikely event the proposed amendments to section 1969 (which are scheduled to go before the Board at a later date) are not adopted and effective before the proposed heavy-duty OBD regulation becomes effective, the proposed heavy-duty OBD regulation includes language detailing basic service information requirements. Additionally, the staff is including language in the proposed OBD regulation that clarifies that, to the extent the service information regulation is effective and operative, it supersedes any redundant service information requirement in the proposed OBD regulation.

IX. CERTIFICATION DEMONSTRATION TESTING REQUIREMENTS

As stated previously, the OBD system is designed to detect malfunctions of the emission control system to help prevent increases in emission levels. The proposed OBD regulation would require manufacturers to design OBD monitors for each emission-related component or system to indicate a malfunction before emissions exceeded a proposed emission malfunction threshold (generally in the range of 1.5 to 5.0 times the applicable standards for most monitors). While the proposed certification requirements (discussed in section X of the Staff Report) would require manufacturers to submit technical details of each monitor (e.g., how each monitor worked, when the monitor would run), ARB staff would still need some assurance that the manufacturers' monitors are indeed calibrated correctly and able to detect a malfunction before the emission threshold is exceeded. Thus, in order to spot-check that the OBD malfunction threshold values set by manufacturers are appropriate, the staff is proposing that manufacturers conduct certification demonstration testing on the major monitors to verify their malfunction threshold values on one to three engines per year. The proposed heavy-duty regulation would require manufacturers to submit documentation and emission data demonstrating that the major monitors are able to detect a malfunction before emissions exceed the emission threshold as part of the proposed certification requirements. In addition to testing the system with "threshold" components (i.e., components that are deteriorated or malfunctioning right at the threshold required for MIL illumination) for the PM filter and NOx aftertreatment system, manufacturers would also be required to test the system with "worst case" components. By testing both the threshold, or best performing failing system, and the worst case, or worst performing failing system, the staff would be better able to verify that the OBD system should perform as expected regardless of the level of deterioration of the component. This could become increasingly important with new technology aftertreatment devices that could be subject to complete failure (such as PM filters) or even to tampering by vehicle operators looking to improve fuel economy or vehicle performance. From staff's analysis of likely combinations of emission hardware, a diesel engine manufacturer would probably need to conduct 8 to 10 emission tests to satisfy these requirements on a single engine and a gasoline engine manufacturer would likely need to conduct five to seven emission tests per engine.

Further, to minimize the test burden on manufacturers, the proposal only requires a few engines to be tested each year for certification demonstration rather than testing of all engines prior to the first time they are certified. By doing this, it is essentially assumed that manufacturers have calibrated the systems correctly on all engines and only a few engines are spot-checked prior to certification each year to make sure. This also spreads the test load out over several years and allows manufacturers to better utilize their test cell resources. The number of test engines manufacturers would be required to conduct certification demonstration testing on would be aligned with the phase-in of OBD in the 2010 through 2013 model years and based on the year and the total number of engine families the manufacturer would be certifying for that model year. Specifically, for the 2010 model year when a manufacturer is only required to implement OBD on a single engine family, demonstration testing would be required on only one engine (a single engine rating within the one engine family).

For the 2011 and 2012 model years, a small manufacturer certifying one to seven engine families would be required to conduct certification demonstration testing on one engine rating per year (one of the other ratings within the engine family that got OBD in 2010). A large manufacturer certifying more than seven engine families would be required to submit data from two engine ratings per year (two of the other ratings within the engine family that got OBD in 2010). Manufacturers would not be required to re-test an engine rating that was tested previously unless substantial emission changes had been made to the engine rating. Additionally, commiserate with the phase-in schedule and in-use liability for 2010 through 2012 model years, a manufacturer will be subject to in-use liability for only the engine rating for which OBD demonstration testing has been completed in 2010. The additional ratings tested in 2011 and 2012 cannot and will not be held to meeting any specified emission levels for the 2010 through 2012 model years. However, the emission data from these additional ratings will still be valuable information for ensuring that manufacturers are using good engineering judgment in calibrating these ratings and in making any mid-course corrections to their engineering judgment in time for the 2013 model year when these ratings do become liable for meeting the emission thresholds.

For the 2013 and subsequent model years, small manufacturers certifying one to five engine families would be required to test one engine rating per year. Medium size manufacturers certifying six to ten engine families per year would be required to test two additional engine ratings per year, and large manufacturers certifying more than ten engine families would be required to test three additional engine ratings per year. Again, commensurate with the phase-in and limited in-use liability in the 2013 through 2015 model years, the engine ratings with in-use liability for meeting the emission thresholds would only be those tested in the 2013 model year. The additional engine ratings tested in 2014 and 2015, like the additional ratings tested in 2011 and 2012, would not be liable for meeting any specified emission levels and the emission results would not jeopardize previous model year or subsequent model year certification. From 2016 model year, all engine ratings would be liable for meeting the emission thresholds and the testing would be used as part of the certification process to ensure compliance.

Given the difficulty and expense in removing an in-use engine from a vehicle for engine dynamometer testing, this demonstration testing would likely represent nearly all of the OBD emission testing that would ever be done on these engines.[23] Requiring a manufacturer, who is fully equipped to do such testing and already has the engines on engine dynamometers for emission testing, to test one to three engines per year would be a minimal testing burden that provides invaluable (and in a practical sense, nearly otherwise unobtainable) proof of compliance with the OBD malfunction thresholds.

Regarding the selection of which engine ratings would be demonstrated, manufacturers would be required to submit descriptions of all engine families planned for the upcoming model year and the Executive Officer would review the information and make the selection(s). For each engine family, the information submitted by the manufacturer would need to identify engine model(s), power ratings, emission standards, emission controls used by the engine, and projected engine sales volume. Factors that would be used by the Executive Officer in selecting the one to three engine ratings for testing include, but are not limited to, new engines, types of emission controls, whether the OBD systems are transitioning to more stringent emission thresholds, and sales volume.

Manufacturers required to submit data from more than one engine rating would be granted some flexibility by being allowed to collect the data under less rigorous testing requirements than the official FTP or ESC certification test. That is, for the second and third engine ratings required for testing, manufacturers would be allowed to submit data using internal sign-off test procedures that are representative of the official FTP or ESC test in lieu of running the official test. Commonly used procedures that would be allowed would include the use of engine emission test cells with less rigorous quality control procedures than those required for the FTP or ESC or the use of forced cool-downs to minimize time between tests. Manufacturers would, however, still be liable for meeting the malfunction thresholds on official tests run according to the FTP or ESC procedure. However, the latitude provided would allow manufacturers to potentially use some short-cut methods that they have developed to assure themselves that the system is calibrated to the correct level without incurring the additional testing cost and burden of running the official FTP or ESC test procedure on every application.

X. CERTIFICATION REQUIREMENTS

The OBD system certification requirements would require manufacturers to submit diagnostic system documentation representative of each engine family. The

[23] While ARB has the authority to conduct in-use testing for enforcement purposes, the limited availability of engine dynamometer facilities and the high cost of removing an engine from a truck that is in service for several weeks at a time severely limits the number of engines and tests that are currently done by ARB.

certification documentation would contain all the information needed for ARB to determine if the OBD system meets the proposed requirements of the heavy-duty OBD regulation. The proposed regulation would list all the information that is required to be in the certification package. If any of the information in the certification package is standardized for all of a manufacturer's engine families (e.g., the OBD system general description), the manufacturer would only be required to submit one set of documents covering the standardized items for all of its engine families per engine model year.

While the majority of the proposed OBD requirements would apply to the engine and be incorporated by design into the engine control module by the engine manufacturer, a portion of the proposed OBD requirements would apply to the vehicle and not be self-contained within the engine. Examples include the proposed requirements to have a MIL in the instrument cluster and a diagnostic connector in the cab compartment. As is currently done by the engine manufacturers, a build specification is provided to vehicle manufacturers detailing mechanical and electrical specifications that must be adhered to for proper installation and use of the engine (and to maintain compliance with emission standards). The staff expects engine manufacturers will continue to follow this model in providing detailed specifications for those items that the vehicle manufacturer will need to be aware of or responsible for to maintain compliance with the proposed OBD regulation. These would include specifications regarding the location, color, and wording of the MIL (as well as electrical connections to ensure proper illumination), location and type of diagnostic connector, and electronic VIN access. During the certification process, in addition to submitting the details of all of the diagnostic strategies and other information required, engine manufacturers would be required to submit a copy of the OBD-relevant build specifications provided to vehicle manufacturers and a description of the method(s) used by the engine manufacturer to ensure vehicle manufacturers adhere to the provided build specifications (e.g., required audit procedures or signed agreements to adhere to the requirements). This is necessary to provide the staff with a reasonable level of certainty that the proposed OBD requirements are indeed satisfied. In summary, engine manufacturers would thus be responsible for submitting a certification package that includes description of all OBD diagnostics performed by the engine control unit (including diagnostics on signals or messages coming from other modules that the engine control unit relies on to perform other OBD diagnostics) as well as a copy of the OBD-relevant build specifications provided to chassis builders and the method used to reasonably ensure compliance with those build specifications.

The proposal would also allow engine manufacturers to establish OBD groups consisting of engine families with similar OBD systems and submit only one set of representative OBD information from each OBD group. The staff anticipates the representative information will normally consist of an application from a single representative engine family. In selecting the representative engine family, the manufacturer would need to consider tailpipe emission standards, OBD phase-in requirements (i.e., if a representative test group meets the most stringent monitoring requirements), and the exhaust emission control components for all the test groups within an OBD group. For example, if one engine family within an OBD group has additional emission control devices, that engine family should be selected as the representative engine family. If one engine family does not adequately represent the entire OBD group, the manufacturer may need to provide information from several engine families within a single OBD group to ensure the submitted information is representative. Manufacturers wishing to consolidate several engine families into an OBD group would be required to get ARB approval of the grouping prior to submitting the information for certification.

Two of the most important parts of the certification package would be the OBD system description and summary table. The OBD system description would include a complete written description for each monitoring strategy outlining every step in the decision-making process of the monitor, including a general explanation of the monitoring conditions and fault criteria. This section may include graphs, diagrams, and/or other data that would help the staff in understanding each monitor. Specific parameter values would be included in the OBD summary table. This table would provide a summary of the OBD system specifications, including: the component/system, the fault code identifying each related malfunction, the monitor strategy, the parameter used to detect a fault and the fault criteria limits to evaluate the parameter (the malfunction criteria and threshold value), secondary parameter values and conditions needed to run the monitor, the time required to execute a monitoring event, and the criteria or procedure for illuminating the MIL. In these tables, manufacturers would be required to use a common set of engineering units to simplify and expedite the review process by ARB staff.

Among the other items that would be required for submittal include: a logic flowchart for each monitor illustrating the step-by-step decision process for determining malfunctions, data supporting the criteria used to detect faults that cause emissions to exceed the specified malfunction thresholds (e.g., 1.5 times the standards) for fuel system, EGR, boost pressure, catalyst, NOx adsorber, PM filter, cold start strategy, secondary air, evaporative system, VVT system, and exhaust gas sensor monitors, data demonstrating the probability of misfire detection by the misfire monitor over the full engine speed and load operating range (for gasoline engines only) or the capability of the misfire monitor to correctly identify a one cylinder out misfire for each cylinder (for diesel engines only), a description of all the parameters and conditions necessary to begin closed-loop fuel control operation (for gasoline engines only), closed-loop EGR control (for diesel engines only), closed-loop fuel pressure control (for diesel engines only), and closed-loop boost control (for diesel engines only), a listing of all electronic powertrain input and output signals (including those not monitored by OBD) that identifies which signals are monitored by the OBD system, detailed descriptions of all the auxiliary emission control device (AECD) strategies used by the manufacturer, and the emission data from the demonstration testing (as described in section IX). The proposed regulation lists the rest of the information that is required to be in the certification package.

XI. PRODUCTION VEHICLE EVALUATION TESTING REQUIREMENTS

Though a manufacturer may "design" an OBD system to fully comply with the OBD regulation, mistakes may occur during the final incorporation of the OBD system into the engine or vehicle. The OBD system is a complex software and hardware system, so there are many opportunities for unintended interactions and other things that can result in certain elements of the system working incorrectly. Staff has seen many such mistakes, which range from OBD II systems unable to communicate any information to a scan tool to monitors that were unable to store a fault code and illuminate the MIL. And though staff acknowledges that heavy-duty vehicles are very different from light- and medium-duty vehicles in terms of emission controls and OBD monitoring strategies, among other things, these types of problems do not depend on these differences, and as such are as likely to occur with heavy-duty OBD as they did with OBD II. Additionally, staff has learned the value of manufacturer self-testing on actual production end products that operate on the road, not pre-production products or individual subsystems that may work fine by themselves but not when they're integrated into a complete product (e.g., due to mistakes like improper wiring).

Thus, the proposed heavy-duty OBD regulation requires manufacturer self-testing on a small fraction of a manufacturer's product line to verify compliance with the OBD requirements. The test requirements are divided into three distinct sections with each section detailing testing for a different portion of the OBD requirements: compliance with the SAE and ISO standardized requirements, compliance with the monitoring requirements for proper fault code storage and MIL illumination, and compliance with the minimum in-use performance monitoring ratios.

A. Verification of Standardized Requirements

An essential part of OBD systems is the numerous standardized requirements that manufacturers have to abide by in their design. The proposed standardized requirements include items as simple as the location and shape of the diagnostic connector (where technicians can "plug in" a scan tool to the on-board computer) to more complex subjects concerning the manner and format in which fault information is accessed by technicians via a "generic" scan tool. The importance of manufacturers meeting these standardized requirements is essential to the success of the heavy-duty OBD program, since it would ensure access for all technicians to the stored information in the on-board computer in a consistent manner. The need for consistency is even higher with the potential incorporation of OBD into the existing heavy-duty inspection program (which would rely on access to the information via a single "generic" scan tool instead of individual tools for every make and model truck that might be inspected at the roadside). In order for inspections to work effectively and efficiently, it is essential that all vehicles are designed *and built* to meet all of the applicable standardized requirements.

While it is anticipated that the vast majority of vehicles would comply with all of the necessary requirements, some problems involving the communication between vehicles and "generic" scan tools may occur in the field as it did for the light- and medium-duty vehicles. From OBD II inspection data, it is estimated that somewhere between 10 percent to 20 percent of the fleet in the initial model years of OBD II implementation did not comply with the standardization requirements, Since implementation of production vehicle testing, it is likely that far fewer than one percent of the fleet has a communication problem. This is attributed to manufacturers conducting post-production testing and being able to identify and correct communication problems while the vehicle is still in production. In the California HDVIP, approximately 15,000 trucks are inspected a year and if just one percent of the fleet failed to comply with standardized requirements, it could result in an additional 150 vehicle owners/operators ending up receiving a citation for a problem actually caused by an improperly manufactured engine and/or truck. On a nationwide scale, it could be a much larger problem. The cause of the problem could range from differing interpretations of the existing standardized requirements to oversights by the design engineers to hardware inconsistencies or last-minute production changes on the assembly line. To try and minimize the chance for such problems on future vehicles and the unnecessary hassles that it could cause vehicle owners/operators, the staff is proposing that engine manufacturers be required to test a sample of production vehicles from the assembly line to verify that the vehicles have indeed been designed and built to the required specifications for communication with a “generic” scan tool.

Under the proposal, starting in the 2013 model year, manufacturers would be required to test “complete” vehicles to ensure that they comply with some of the basic “generic” scan tool standardized requirements, including those that are essential for proper inspection. Ideally, manufacturers would be required to test one vehicle for each truck and engine model combination that is introduced into commerce. However, for a large engine manufacturer, this could be in the neighborhood of 5,000 to 10,000 unique combinations. As such, since it would be unreasonable to require testing of every combination, the proposal would only require manufacturers to test 10 combinations per engine family. Given that an engine family typically has five different engine ratings, this works out to testing of only two vehicles per engine rating. Under this proposal, a large manufacturer would be required to only test about 1.5 percent to 3.0 percent of their unique combinations or about 150 vehicles. Specifically, manufacturers would be required to test one vehicle per software "version" released by the manufacturer. With proper demonstration, manufacturers would be allowed to group different calibrations together and test one vehicle that is representative of the group. The regulation would require engine manufacturers to submit for ARB review and approval a test plan that verifies the vehicles tested would be representative of all vehicle configurations (e.g., each ECM variant coupled with and without the other available vehicle components that could affect scan tool communication such as automatic transmission or hybrid powertrain control modules). The plan would include details on all the different applications and configurations that would be tested.

Additionally, manufacturers would be required to conduct this testing on actual production vehicles, not stand-alone engines. In the past, the staff found that light-duty vehicles that do not properly communicate with a scan tool or I/M equipment cause huge problems at repair facilities and I/M stations, since technicians are unable to access all of the necessary emission-related information from the vehicle's on-board computer. In fact, it is such a egregious issue that under the light- and medium-duty OBD II enforcement regulation (section 1968.5), this specific problem has been identified as one that would result in mandatory recall. Thus, to avoid this problem with heavy-duty vehicles, it is imperative that the proposed testing be representative of all applications. Further, the staff has also had numerous issues in the past with light-duty vehicles where, despite each controller independently working properly, interaction problems between two controllers (e.g., ECM and TCM) have caused communication problems with scan tools, such as lack of communication or communication with only one module. In this case, separate testing of the controllers would be blind to this problem. There have even been cases where interaction problems between emission-related controllers and non-emission-related controllers (e.g., ABS, airbag) have caused scan tool communication problems. Since heavy-duty engine manufacturers are expected to sell the same engine (with the same calibration) to various vehicle manufacturers who would put them in different final products (e.g., with different TCMs), the same communication problem would be expected to occur. Furthermore, on some occasions, the staff has found applications that communicated properly with generic scan tools during development but last minute production changes (such as component supplier changes, etc.) have caused actual production vehicles to differ from pre-production development vehicles and to not properly communicate. Thus, for heavy-duty vehicles, it would be necessary to have proposed testing done on the end vehicle product, not just the engine, and to have the proposed testing be representative of all possible configurations of controllers.

Verification testing of standardized requirements should occur soon enough in the production cycle to provide manufacturers with early feedback of the existence of any problems and time to resolve the problem prior to the introduction of the entire model year of engines being introduced into the field. The proposed regulation would require that testing of vehicles be done and data submitted to ARB within either three months of the start of normal <u>engine</u> production or one month of the start of vehicle production, whichever is later.

To verify that all manufacturers are testing vehicles to the same level of stringency, the proposed regulation would require the engine manufacturers to get ARB approval of the testing equipment used by the manufacturer to perform this testing. ARB approval of the testing equipment would be based upon whether the equipment can verify that the OBD system complies with the standardized requirements and will likely communicate properly with any off-board test equipment (e.g., generic scan tools) that is also designed to meet the standardized requirements. The staff anticipates that the engine manufacturers and scan tool manufacturers will likely develop a common piece of hardware and software which could be used by all engine manufacturers at the end of the vehicle assembly line to meet this requirement. Two different projects (SAE J1699 and LOC3T) have developed such equipment under the light-duty OBD II requirements. The equipment is currently being used to test 2005 and 2006 model year light- and medium-duty vehicles, and similar type equipment could be developed in time for the 2013 model year for the heavy-duty industry and communication standards selected.

Ideally, this test procedure will verify each and every requirement of the communication specifications including the various physical layers, message structure, response times, and message content.

It is important to note, however, that this verification equipment would not replace the function of existing "generic" scan tools used by technicians or roadside inspectors. This equipment would be custom-designed and used expressly for the purposes of this assembly line testing and would not include all of the necessary features for technicians or inspectors.

B. Verification of Monitoring Requirements

The proposed OBD regulation would require comprehensive monitoring of virtually every component on the vehicle that can cause an increase in emissions. To accomplish this task, manufacturers would need to develop sophisticated diagnostic routines and algorithms that are programmed into software in the on-board computer and calibrated by engineers. This would translate into thousands of lines of software programmed to meet the diagnostic requirements but not interfere with the normal operation of the vehicle. While most manufacturers would likely develop extensive verification or "sign-off" test procedures to ensure that the diagnostics function correctly, problems could and will probably happen. Moreover, the majority of the validation testing done by the manufacturer would probably focus on finding problems that would be noticed by the vehicle operator such as those that will cause the MIL to falsely illuminate when no malfunction really exists rather than verifying that the MIL will indeed illuminate when a malfunction does exist.

The problems that occur could vary greatly in severity from essentially trivial mistakes that have no noticeable impact on the OBD system to situations where significant portions of the OBD system and normal vehicle fuel and emission control system are disabled. Furthermore, it is often very difficult to assess the impact the problem may or may not have on vehicles that will be on the road for the next 10-30 years. The cause of the problems could also vary from simple typing errors in the software to carelessness to unanticipated interactions with other systems or production or component supplier hardware changes.

In an attempt to minimize the chance for significant problems going undetected and to ensure that all manufacturers are devoting sufficient resources to verifying the performance of the system, the staff is proposing that engine manufacturers be required to perform a thorough level of validation testing on one to six actual production engines and vehicles per model year and submit the results to ARB. Additionally, similar to the demonstration testing requirement (section IX. of the Staff Report), the number of engines and vehicles engine manufacturers would be required to test would be based on the total number of engine families the manufacturer would be certifying for that model year. Specifically, an engine manufacturer certifying one to five engine families in a model year would be required to conduct testing on one engine and one vehicle from two engine families. An engine manufacturer certifying six to ten engine families would be required to conduct testing on two engines and two vehicles from four engine families. Lastly, an engine manufacturer certifying more than ten engine families would be required to conduct testing on three engines and three vehicles from six engine families. The test engines would be from the specific engine code and engine family combination chosen for the demonstration testing, while the Executive Officer would select the test vehicle variants to be tested by the manufacturer from the information submitted by the manufacturer.

For the testing, engine manufacturers would be required to individually implant or simulate malfunctions to verify that virtually every single engine-related OBD diagnostic on the vehicle correctly identifies the malfunction. Prior to testing, manufacturers would be required to submit a test plan for review and approval by the Executive Officer detailing the method used to implant each fault and verify proper diagnostic operation. The Executive Officer would exempt manufacturers from testing that could not be done without causing physical damage to the production vehicle. The testing would be required to be completed and reported to ARB within six months after a manufacturer begins normal engine production to provide early feedback on the performance of every diagnostic on the vehicle. Upon good cause, the Executive Officer may extend this time period for testing.

As an incentive to perform this thorough validation testing, a manufacturer could request that any problem discovered during this self-testing be evaluated as a deficiency and take effect retroactively to the start of production of the engine. If the other factors necessary to qualify for a deficiency are indeed satisfied, the Executive Officer would amend the certification to retroactively assign the deficiency to the start of production of the affected engines. In contrast, problems discovered later by ARB staff during in-use testing would become noncompliance issues and handled in accordance with OBD-specific enforcement regulations.[24]

C. Verification and Reporting of In-use Monitoring Performance

The staff is proposing that manufacturers track the performance of several of the most important monitors on the vehicle to determine how often they are executing during in-use operation. These requirements are discussed in more detail in section VII of the Staff Report. Essentially, the proposed regulation would standardize a method for measuring and determining how often monitors are executing in the real world and set a minimum acceptable performance level. Monitors that perform below the acceptable levels would be subject to remedial action including potential recall.

[24] While the regulatory package being considered for adoption does not currently include a separate OBD-specific enforcement regulation due to time and resource constraints, the staff intends to come back to the Board with a proposed enforcement regulation prior to the introduction of OBD systems on heavy-duty vehicles. It is the staff's intention to have a stand-alone OBD enforcement regulation, analogous to the separate OBD II enforcement regulation for light-duty vehicles, title 13 CCR section 1968.5. See section II of the Staff Report for more details.

In conjunction with the proposal to measure in-use monitoring frequency, the staff is also proposing that manufacturers be required to collect these in-use data within the first six months after vehicles with the engine family were first introduced into commerce. This information would provide ARB with early indication as to whether or not the system is performing adequately as well as provide valuable feedback as to the appropriateness of the minimum ratio. As discussed in section VII, the staff is proposing a ratio of 0.100 primarily because a sufficient database does not currently exist that would allow the staff to develop a more accurate estimate of fault detection in a reasonable time period such as two weeks. The requirement for manufacturers to collect and report some of these data in the early years would provide an invaluable source of real world data and allow the staff to revise the regulatory requirements as necessary to establish a ratio that more closely correlates with the desired in-use monitoring frequency.

Prior to acquiring these data, engine manufacturers would be required to submit for ARB review and approval a sampling plan that verifies that the data collected would be representative of California driving for all applications (e.g., buses, long-haul trucks) the engine families are used for. The plan would detail all applications that employ the engines, the number of engines per application group that would be tested and the method in which the data would be collected. Manufacturers would be required to submit frequency data from a sample of at least 15 vehicles. Discussing the plan with ARB would allow each manufacturer to identify the most cost-effective way to obtain the data. Some manufacturers may find it easiest to collect data from vehicles that come in to its authorized repair facilities for routine maintenance or warranty work during the time period required, while others may find it more advantageous to hire a contractor to collect the data. Further, upon good cause, the Executive Officer may extend the six-month time period for the collection of data to cover situations where manufacturers have difficulty in gathering the required data within the six-month time period.

As stated before, the data collected under this program are primarily intended to provide an early indication that the systems are working as intended in the field, to provide information to "fine-tune" the proposed requirements for tracking the performance of monitors, and to provide data to be used to develop a more appropriate minimum ratio for future regulatory revisions. The data are not intended to substitute for testing that would be performed by ARB under the future heavy-duty OBD-specific enforcement regulation to determine if a manufacturer is complying with the minimum acceptable performance levels established in the OBD regulation. In fact, the data collected would not likely meet all the required elements for testing by ARB to make an official determination that the system is noncompliant.

XII. DEFICIENCIES

As discussed in the introduction, the proposed OBD regulation would require monitoring of virtually all components and systems that can affect vehicle emissions. Most components and systems would be monitored for more than one type of failure. Therefore, OBD systems would contain many diagnostic algorithms. During the early stages of OBD implementation for light- and medium-duty vehicles, some manufacturers encountered unforeseen and generally last minute problems with some monitoring strategies despite a good faith effort to comply with the requirements in full. The staff anticipates the same problems to occur during heavy-duty OBD implementation.

Thus, like the light- and medium-duty OBD regulation, the staff is proposing a provision that would permit certification of heavy-duty OBD systems with “deficiencies” in cases where a good faith effort to fully comply has been demonstrated. Specifically, in granting deficiencies, the Executive Officer would consider the following factors: the extent to which the proposed requirements of the OBD regulation are satisfied overall based on the application review, the relative performance of the resultant OBD system compared to systems fully compliant with the proposed requirements of the OBD regulation, and a demonstrated good-faith effort on the part of the manufacturer to: (1) meet the proposed requirements in full by evaluating and considering the best available monitoring technology; and (2) come into compliance as expeditiously as possible.

The deficiency provisions would facilitate OBD implementation by mitigating the danger of manufacturers not being able to certify engines with relatively minor implementation problems. However, to prevent misuse of the provision and ensure equity for manufacturers able to meet the proposed requirements in full, the staff is proposing that for 2013 and subsequent model year engines, manufacturers would be subject to fines for deficiencies in excess of two for a particular model. The fines would be in the amount of $25 or $50 per deficiency per engine depending on the significance of the monitoring strategy in question. Given the leadtimes proposed for the monitoring requirements and the experience of light- and medium-duty OBD compliance, the staff is anticipating very few engines that would be subject to fines. For 2010 through 2012 model year engines, manufacturers would be allowed unlimited “free” deficiencies.

There has been some confusion by manufacturers as to the purpose of deficiencies. Specifically, several have expressed a belief that deficiencies are used by ARB to relax the OBD regulation if any of the proposed monitoring requirements turn out to be technically infeasible or require a higher malfunction criteria to be feasible. However, deficiencies are not used for this purpose. If subsequently gained experience or knowledge does indeed prove out that a monitoring requirement or malfunction criteria needs revision to be technically feasible, two mechanisms exist to address that. First, section (g)(6.1) gives specific authority to the Executive Officer to “revise the emission threshold for any monitor in sections (e) through (g) if the most reliable monitoring method developed requires a higher threshold to prevent significant errors of commission in detecting a malfunction”. This provision exists to address any unforeseen problems in meeting the malfunction criteria proposed by staff. Secondly, given the technology-forcing nature of an OBD regulation, the Board has historically directed the staff to report back on a biennial basis on the status of manufacturer’s progress towards meeting the requirements and to propose any necessary updates or amendments to the regulation at that time. Such regulatory updates are again expected to occur for heavy-duty OBD and it is likely that at least two will be done (in 2007 and 2009) prior to the first introduction of a heavy-duty OBD system in 2010 model year.

XIII. ANALYSIS OF ENVIRONMENTAL IMPACTS AND ENVIRONMENTAL JUSTICE ISSUES

Foremost, the proposed regulation helps ensure that forecasted emission reduction benefits from adopted heavy-duty engine emission standards programs are achieved. Given the substantial shortfall in emission reductions still needed to attain the National and State Ambient Air Quality Standards and the difficulty in identifying further sources of cost-effective emission reductions, it is vital that the emission reductions projected for the heavy-duty vehicle programs be achieved. The proposed OBD regulation is necessary to accomplish this goal. Monitoring of an engine's emission control system through the use of OBD systems helps guarantee that engines initially certified to the stringent emission standards maintain their performance throughout the entire engine life. It would make little sense to require very low emissions from new engines and then allow them to deteriorate to much higher levels as they age. The proposed regulation achieves these emission benefits in two distinct ways. First, to avoid customer dissatisfaction that may be caused by frequent illumination of the MIL because of emission-related malfunctions, it is anticipated that the manufacturers will produce increasingly durable, more robust emission-related components. Second, by alerting vehicle operators of emission-related malfunctions and providing precise information to the service industry for identifying and repairing detected malfunctions, emission systems will be quickly repaired. The benefits of the proposed OBD regulation become increasingly important as certification levels become more and more stringent and as a single malfunction has an increasingly greater impact relative to certification levels.

For the analysis, staff used the ARB emission model, EMFAC, to estimate failure rates and emission impacts for various emission-related components in the heavy-duty fleet. All failures that occur during the warranty period were assumed to be repaired while after the warranty period, thirty percent of the detected malfunctions were assumed to be repaired. While there is no I/M program in place for heavy-duty vehicles, the fleet self-inspection rule and HDVIP do test a significant portion of the fleet and cause repair of detected problems. Further, many of the malfunctions that would be detected by the OBD system also result in a reduction in fuel economy, engine performance, or even engine durability. Accordingly, it is anticipated that a portion of the vehicle operators will seek repair of a detected malfunction to restore fuel economy and engine performance.

As mentioned above, OBD systems achieve benefits in two ways. The first mechanism is by encouraging design of robust emission control systems to meet the 2010 emission standards (and avoid MIL illumination). The second is by alerting vehicle operators to the presence of a malfunction and thus, triggering repair. However, there is no easy method to quantify the amount of emission reduction attributable to OBD for the first mechanism. In theory, a portion of the emission benefits assigned to the 2010 emission standards should be reassigned to the OBD system to reflect this but staff is not aware of a reasonable manner to calculate what this portion is. As such, this emission benefit, although real and likely significant, is ignored for this analysis. To calculate the emission benefits from the second mechanism, staff analyzed the current inspection programs applicable to heavy-duty vehicles and the proposed monitoring requirements as well as estimated failure rates for various emission control components and expected repair rates. The analysis focused on the benefit of identifying heavy-duty vehicles in need of repair after the engine manufacturer's warranty had expired and the resultant emission benefit from those repairs.

The methodology used by staff to estimate the emission reductions was to estimate failure rates of various emission control components (and the associated emission increases with those failures) and then calculate the difference between the percentage of those failures that would be repaired with and without an OBD system. The emission benefits were then calculated from the additional repairs caused by the presence of the OBD system.

For this analysis, staff utilized ARB's emission model (EMFAC) to estimate the emission benefits for future model year vehicles (e.g., 2010 and subsequent model year). Within the EMFAC model for the heavy-duty fleet, tables exist that allow the user to input various emission component malfunction rates and the associated emission rates with each of those component malfunctions. Staff modified several of the existing components to better reflect the technology that is expected to be used on 2010 and subsequent engines. Specifically, staff added malfunction categories for PM filter leaks, missing/tampered PM filters, NOx aftertreatment system malfunctions, and NOx aftertreatment control sensor malfunctions. To make room for these categories, staff eliminated the categories for puff limiter misset, puff limiter disabled, and EGR stuck open and merged minor, moderate, and severe injector problems into a single category as well as expanded EGR disabled to include EGR low flow/performance malfunctions.

<u>Malfunction Emission Rates</u>

Staff also modified the associated emission rates for each of the malfunction categories to better reflect the best estimates available at this time based on the expected 2010 and subsequent emission control systems. For the existing categories, staff reduced the estimates for PM emission increases by a factor of 0.95 based on the expectation that all 2010 engines will be equipped with a PM filter which will trap 95 percent of any engine out increases in PM. For the added categories of PM filter leaks and PM filter missing/tampered, staff estimated PM increases of 600 percent and 1000 percent, respectively. For the PM filter leaks, this represents an emission level of 0.07 g/bhp-hr which is above the OBD threshold of 0.05 g/bhp-hr but reflects industry's contention that most PM filter leaks will rapidly grow beyond a small leak. For the PM filter missing/tampered, staff estimated the emissions would approach that of an engine without a PM filter for an increase of 1000 percent.

For HC emission rates for the existing categories, staff estimated the presence of larger oxidation catalysts to achieve sufficient exotherms for PM filter regeneration would convert 50 percent of any increases in engine out HC rates and thus reduced the HC emission increases by a factor of 0.5. For the added categories related to PM filters and malfunctions associated with NOx aftertreatment or the aftertreatment control sensors, staff assumed a small HC increase due to reduced conversion of HCs within the PM trap itself or improper reductant malfunctions (e.g., overdosing fuel in a NOx adsorber system). For a malfunction of the oxidation catalyst itself, staff assumed a 50 percent increase in HC emissions.

For NOx emission rates for the existing categories, staff estimated that engine out NOx increases would be reduced by the presence of NOx aftertreatment to varying degrees. For smaller engine out NOx increases, the aftertreatment was estimated to convert 75 percent of the excess NOx (thus reducing the emission rate by multiplying by a factor of 0.25). For larger engine out NOx increases, a slightly reduced aftertreatment conversion efficiency (65 percent) was used to reflect a reduced ability in the system to handle large feedgas concentration increases. For the added categories of NOx aftertreatment control sensors, an emission increase of 200 percent (to a tailpipe emission level of 0.6 g/bhp-hr NOx) was assigned based on the assumption that a loss of feedback control (either a NOx sensor for SCR or an A/F sensor for an adsorber) would result in significantly lower NOx conversion rates because a manufacturer would likely shut off reductant delivery or go to a very conservative open loop control system that injected minimal reductant to minimize the risk for overdosing. For the added category of NOx aftertreatment, a failure was calculated to have a 300 percent increase to reflect a tailpipe emission level of 0.8 g/bhp-hr NOx). This represents an intermediate level between a MIL-on failure (at 0.5 g/bhp-hr) and a complete loss of NOx aftertreatment (at 1.2 g/bhp-hr). Considering that this category includes failures of the SCR catalyst or adsorber itself as well as failures of the reductant delivery system (in exhaust injectors, reductant tank, reductant delivery lines, reductant metering, reductant heaters, and compressed air delivery system), many of which would likely result in the manufacturer shutting off reductant delivery or defaulting to open loop operation, the emission increase of 300 percent is appropriate. Lastly, while EMFAC already included a category for EGR malfunctions, the NOx emission increase associated with an EGR failure was a 0.0 percent increase. This was modified to a NOx emission increase of 150 percent to a tailpipe level of 0.5 g/bhp-hr NOx. This emission rate was calculated by assuming a complete loss of EGR would cause engine out NOx to go from 1.2 to 2.4 g/bhp-hr for an increase of 1.2 g/bhp-hr and then assuming that the NOx aftertreatment would convert 60 percent of that increase leaving a tailpipe increase of 0.48 g/bhp-hr. Thus, EGR failures were estimated to range from the OBD MIL on point of 0.3 g/bhp-hr to a complete loss of EGR at 0.68 g/bhp-hr and a nominal middle point is 0.5 g/bhp-hr.

<u>Malfunction Occurrence Rates</u>
Staff also estimated various failure rates for the categories of components which were then translated to a weighted average failure rate in the fleet as EMFAC is set-up to use. For the existing categories in EMFAC, staff did not modify the estimated failure rates. However for the added and modified categories, staff estimated failure rates based on information from manufacturers, suppliers, and, where appropriate, experience with similar components in light-duty.

For EGR, staff increased the failure rate from 10 percent to 20 percent to account for nearly every engine using EGR in the 2010 timeframe. For the oxidation catalysts, staff increased the failure rate from 1 percent to 5 percent to account for nearly every engine being equipped with a catalyst and to account for combining catalyst performance malfunctions with catalyst tampered/removed into a single category.

For the added category of PM filter leak, staff estimated a failure rate that increased over time starting with an approximately 6 percent failure rate at the end of useful life (~450,000 miles) and ramping up to a failure rate of 37 percent at 1,000,000 miles. In setting this failure rate, staff did not use the higher failure rates currently being observed in the small portion of the PM filter equipped heavy-duty fleet (both OEM-equipped and retrofit) because those failures are predominately related to plugging of the filter (not leaks) and not representative of the fully integrated and optimized designs expected to be used in the 2010 and subsequent model years. For the category of PM filter disabled (largely due to tampering), staff assumed a rate of only 2 percent.

For the category of NOx aftertreatment which includes the SCR catalyst or adsorber itself as well as all components associated with reductant storage and delivery to the exhaust, staff estimated a failure rate that increased over time. The failure rate was ramped in starting with a 10 percent failure rate at 500,000 miles to a 50 percent failure rate by 1,000,000 miles. While failures of an SCR catalyst itself may be fairly limited, the associated hardware include urea tank, tank heaters, in-exhaust injector, compressed air delivery to the injector, and urea supply pump and control system are all components subject to malfunction. To assume that only half of the trucks left on the road at 1,000,000 miles will have experienced a failure of any one of these components at some point in its 1,000,000 mile life is fairly conservative. For an adsorber system, the adsorber itself will likely have a significant failure rate in a 1,000,000 mile timeframe given the sensitivity to thermal damage and the need for periodic desulfation that must be conducted at temperatures extremely close to the thermal damage point. Further, each desulfation event will likely slightly deteriorate the performance of the adsorber leading to an eventual fail on some share of the engines. Adsorber systems also rely on in-exhaust injectors and fuel supply lines, control, and metering systems that are subject to malfunction.

For the NOx aftertreatment control sensors category (e.g., NOx sensor, A/F sensor), a two-part failure rate was estimated. First, a single failure of the control sensor was estimated to ramp in starting with a 35 percent failure by 250,000 miles and peaking at a 90 percent failure rate by 450,000 miles. Staff based these failure rates on discussions with manufacturers expressing concern that they had not been convinced that NOx sensor durability was sufficient to last 100,000 miles, much less the useful life period of 450,000 miles. Further, A/F sensors are commonplace in light- and medium-duty vehicles and Inspection and Maintenance program data indicates these sensors are failing in I/M on approximately 2.5 percent of the fleet at 100,000 miles. Assuming this failure rate were to stay constant from 100,000 miles to 250,000 miles, that would represent a cumulative failure rate of 15 percent at 250,000 miles. When adjusting that number to reflect the more realistic situation that the failure rate increases over time, a

35 percent failure rate at 250,000 miles is reasonable. To assume that 90 percent of the sensors have failed once by the end of useful life is consistent with a continued increase of the failure rate and manufacturers' expressed opinions that the sensors will not last through the useful life.

The second part of the failure rate estimates the percentage of the fleet that will repair/replace the failed sensor and then experience a subsequent failure of the repair/replaced sensor while still within the first 1,000,000 miles of the engine life. For this failure rate, staff assumed the same sensor durability and failure rate (rate ramps up from 35 percent to 90 percent and begins 250,0000 miles after the previous sensor repair/replacement) but only applied it to the fraction of vehicles which were estimated to already have a failed sensor and a subsequent repair.

<u>OBD Repair Rate</u>
While the component malfunction rates input into EMFAC are a single number that represents a weighted failure rate, or probability of occurrence, the model actually assumes that there are constantly some additional failures and repairs that are occurring in the fleet. As such, the single failure rate number represents that average that are currently in a malfunctioning state in the fleet at a given point in time. For the baseline (without OBD) scenario, these numbers represent the failures that are above and beyond what is being routinely repaired in the field.

For the "with OBD" scenario, EMFAC was re-run with a 30 percent reduction in component failures across all categories to simulate an additional 30 percent of the malfunctions that are repaired due to the presence of the OBD system. Staff's rationale for the 30 percent repair rate was that all the malfunctions estimated in EMFAC would result in MIL illumination. It is expected that some fraction of vehicle owners or operators would take repair action simply because they were alerted to the presence of a malfunction by the MIL. Additionally, California has two inspection programs that are applicable to heavy-duty vehicles. First, the heavy-duty vehicle inspection program (HDVIP) conducts roadside testing and issues citations or notice-of-violations for trucks that fail either a snap-idle opacity test or a visual inspection. This inspection program currently tests about 6 percent of the heavy-duty fleet in California. Secondly, California has a fleet annual self-inspection program whereby all fleets (defined as anybody with two or more trucks) are required to perform self-inspections for snap-idle opacity on an annual basis, repair any vehicles that fail the inspection, and retain records of the inspection for review by ARB inspectors. Currently, about 75 percent of the Californa fleet is subject to this fleet self-inspection. While both programs are currently focused on smoke emissions and visual tamper inspections, it is expected that they will be updated to also include an inspection of the OBD system and to fail vehicles that have an illuminated MIL. When combining these three factors together (response to an illuminated MIL, HDVIP inspections, and fleet self-inspections), it seems fairly conservative to expect that 30 percent of the illuminated MILs will be repaired.

EMFAC Modeling Results
Using the modified failure rates and emission rates for the failures, EMFAC was used to estimate the baseline fleet and per engine cumulative emissions absent an OBD system. 2010 model year engines were modeled (but the result would be the same for any subsequent model year because the emission standards do not change beyond the 2010 model year). The emissions were calculated over the first 21 years that the engine is in service. 21 years was selected because it was the point that the heaviest category of heavy duty engines reaches 1,000,000 miles and also represents the point where 50 percent of the engines are still in service (i.e., 50 percent of the 2010 model year engines are still be used on the road in the year 2031 and the average mileage on the engine at that point is 1,000,000 miles).

Based on this analysis, OBD was calculated to generate a statewide benefit of 1.5 tons/day (tpd) of ROG, 109 tpd of NOx, and 0.6 tpd of PM in calendar year 2020. Lifetime cumulative emission reductions on a per engine basis were calculated to be 81 pounds of ROG, 5,735 pounds of NOx, and 24 pounds of PM.

Having identified that the proposed regulation will not result in any adverse environmental impacts but rather will help ensure that measurable emission benefits are achieved statewide, the regulation should not adversely impact any community in the State, especially low-income and minority communities.

XIV. COST IMPACT OF THE PROPOSED REQUIREMENTS

The cost analysis is divided into two sections. The first section covers the costs that an engine manufacturer would incur in developing and implementing the OBD requirements and the retail price increase of an engine as a result of that. The second section covers the costs that a vehicle owner are expected to incur in the form of repair costs as a result of the OBD system. In addition to this summary, actual Excel files detailing the cost analysis is listed in the references and is available for review from ARB.

A. Cost of the OBD System

ARB staff has performed a comprehensive cost analysis of the proposed heavy-duty OBD program. The goal of this analysis is to estimate the “learned-out” costs of the program to a heavy-duty engine purchaser for a “typical” engine. The analysis includes estimates of the incremental costs of implementing the heavy-duty OBD program for a “hypothetical” larger-than-average engine manufacturer. Since the internal corporate costs of implementing the heavy-duty OBD program are closely guarded by individual engine manufacturers and can vary significantly within the industry, ARB staff made assumptions regarding the corporate structure of the typical manufacturer. The ARB cost estimates assume that the typical engine manufacturer is a low-cost horizontally-integrated company, i.e., one that relies heavily on suppliers to assist in the development and production of engines. Manufacturers rely on these suppliers to produce the final components rather than source the parts through their own internal facilities to achieve the lowest costs. The various types of costs that are addressed in this analysis are variable costs, support costs, investment recovery costs, capital recovery costs, and truck/coach builder costs. Results of the analysis indicate the learned-out costs per engine to incorporate the proposed heavy-duty OBD regulation would be $132.39 for diesel engines and $35.04 for gasoline engines. Details of the cost analysis methodology used to estimate the diesel and gasoline engine costs are discussed in the following sections.

<u>Diesel Engine Cost Analysis</u>

To conduct the cost analysis for diesel engine manufacturers, staff assumed a slightly larger-than-average hypothetical manufacturer in terms of the number of engine families and ratings or variations per engine family. This assumption provides a conservative "average" cost per engine to represent the costs to develop and calibrate the heavy-duty OBD systems. The hypothetical engine manufacturer is projected to have a product line consisting of four engine displacements, two engine families per engine displacement, and five ratings per engine family. This assumption results in eight total engine families and 40 total engine ratings for the hypothetical engine manufacturer. In contrast, the "average" engine manufacturer according to U.S. EPA's data of 2004 heavy-duty engines includes four engine displacements, 6.5 engine families, and five ratings per engine family which results in 32.5 total engine ratings. To determine the average sales number of the hypothetical manufacturer, the staff took the national sales numbers for the top nine engine manufacturers and determined a composite average value of 72,440. This number was rounded to 72,000 in the analysis.

Variable Costs

In this section, the cost of new parts added to HDOBD engines, additional assembly operations, any increases in the cost of shipping parts, and any new warranty implications are addressed.

Cost of Additional Hardware

The first step in assessing costs was to define the systems and technologies likely to be used by manufacturers to meet the 2010 emission standards. Based on discussions with U.S. EPA, industry, researchers, and consultants, a consensus was formed on the most likely emission system configurations that will be utilized to comply with 2010 emission standards. Most believe that diesel engine manufacturers will utilize EGR systems and other engine emission controls to reduce engine-out emissions as much as possible and include PM filters, oxidation catalysts, and either SCR catalysts or NOx adsorbers to further reduce emissions in order to comply with the stringent standards. As such, staff assumed that all 2010 engines will include cooled EGR, an oxidation catalyst, PM filter, and SCR catalyst or NOx adsorber. As discussed in the technical feasibility section (section IV. of the staff report), PM filters are not projected to require any additional sensors for monitoring purposes, the oxidation catalyst is projected to require the addition of a temperature sensor, and the NOx adsorber or the SCR catalyst would be monitored with the same NOx or A/F sensors used for control. Once the technologies for meeting the 2010 emission standards were identified, the staff estimated the percentage of these technologies that would be required to comply with the heavy-duty OBD requirements for the 2016 model year. The 2016 model year was chosen for the analysis because that is the year where all of the requirements of the HDOBD regulations are fully phased in on all engine ratings in all engine families except for alternative-fueled engines and therefore provides a “worse-case” scenario for the analysis. The staff then compared the technology assessments with that of ARB and U.S. EPA’s technology assessments for the 2010 emission standards rulemaking to determine the incremental cost of added hardware for implementing a heavy-duty OBD system. Since the 2010 emission standards rulemaking conducted a few years ago, some of the technologies projected to be needed to meet the 2010 standards have changed. Accordingly, staff adjusted the incremental costs of OBD hardware based on current projections for 2010 technologies. For example, the costs of mass air flow (MAF) sensors and air-fuel ratio (A/F) sensors for EGR system control were not included in the 2010 rulemaking and were, therefore, included in the cost of OBD. Also, while NOx adsorbers were previously projected to be the predominant NOx aftertreatment device, SCR catalysts are now considered the more likely NOx aftertreatment approach to be used on 2010 engines. Table II-1 lists the technologies and application rates that staff projects for engines to comply with the HD OBD requirements and the associated costs to the manufacturers.

Cost of Assembly

Other variable costs include costs of assembly, shipping, and warranty. Costs to assemble OBD systems for heavy-duty engines are not expected to be much different than those for engines without OBD systems. The additional assembly costs for the majority of engines are installation of temperature sensor bosses for an oxidation catalyst, PM filter regeneration, and EGR cooler monitoring, and installation of MAF sensor flanges for EGR system monitoring. Staff assumes some vehicles will require installation of A/F sensor bosses for EGR monitoring and injection quantity monitoring.

Cost of Shipping

Shipping costs for heavy-duty OBD engines are projected to be nearly the same as non-OBD engines. This is because for the majority of engines, only a MAF sensor, dual exhaust temperature sensors, and an EGR cooler temperature sensor would be added to the engine assembly. A smaller number of engines that include a NOx adsorber and/or utilize more innovative methods for controlling EGR may require four additional A/F sensors. The cost of shipping the various sensors was estimated to add $0.30 each to the cost of the system (assuming that sensors will be shipped in bulk to the manufacturer).

Cost of Warranty

Warranty costs should also be minimal. Based upon the durability of heavy-duty engines and data from OBD II-equipped medium-duty vehicles, we project that the failure rate for the added sensors and components will range from 0.05 percent to one percent within the 100,000 mile warranty period. The replacement cost of the various sensors and components were adjusted by twenty percent to account for the added cost of purchasing the replacement parts at smaller quantities compared to the production parts, cost of shipping and handling, administration costs, and dealer costs. The assembly, warranty and shipping costs are summarized in Tables II-2.

Support Costs

Support costs affecting the retail price of heavy-duty OBD modifications are estimated to include research costs, engineering support costs, legal resources, and administrative increases.

Research Costs

Research costs include the engineering and other labor costs (e.g., technicians) needed to develop and calibrate the base heavy-duty OBD algorithms. To determine the research costs, staff assumed a hypothetical 2016 model year engine with cooled EGR, VGT, oxidation catalyst, PM filter, and an SCR catalyst. An SCR catalyst-based system was assumed since it is projected to require the most monitors and would provide a worst-case cost scenario. From this hypothetical engine, staff estimated the number and types of monitors that would be required for the OBD system. Each of the monitors was categorized into one of twelve diagnostic categories. The twelve diagnostic categories are assumed to represent the different type of monitors in the hypothetical 2016 system. All monitors were categorized with the exception of circuit continuity diagnostics, since these diagnostics are already included in EMD systems which are required on all 2007 and subsequent model year vehicles by a previous regulation. Each of the diagnostic categories was individually assessed for the engineering and test times needed to develop and calibrate the heavy-duty OBD system. For example, staff projects that the PM filter performance/leak diagnostic will be the most difficult monitor to develop and calibrate while the oxidation catalyst monitor will be considerably less complex. As such, staff's analysis projects that four engineers will be needed to develop the PM filter diagnostic algorithm and 12 staff (i.e., engineers and technicians) will be required to calibrate the diagnostic for the hypothetical engine manufacturer used in this analysis. In contrast, the oxidation catalyst is projected to require one engineer to develop the algorithm and two staff to calibrate the diagnostic.

The staff assumed an eight-step process to develop the base algorithm for each diagnostic on one engine rating. The eight steps include determining the emissions impact of failures, developing failure mode effects analysis (FMEA), developing the diagnostic concept, limit/threshold part development, prototype/concept testing, validation, sensitivity analysis, and tuning guide development. It is assumed that a manufacturer will develop a single base algorithm that can be applied across every engine displacement, engine family, and associated engine rating within the manufacturer's product line-up without modifications to the algorithm. Staff also assumed that manufacturers will develop the algorithm on a pre-production engine that is close to production intent (i.e., hardware and emission calibrations are close to its final production version). Staff believes that developing the algorithm on an engine that is not near its production state will be inefficient and would unnecessarily require significant redevelopment work when applied to the production engine.

To adjust the base algorithm to work on other engine families and ratings, each algorithm will need to be individually calibrated. Staff assumed a three-step process to calibrate each diagnostic on subsequent engine families and ratings. Utilizing the tuning and validation guide developed during the algorithm development process, the three steps include review FMEA, test limit parts and nominal parts, and validation. The costs to calibrate other engine families and ratings within an engine family were discounted with factors that took into account the similarity of engine designs relative to the base engine used to develop the algorithm since the amount of engineering and testing work should be less on similar engines. The life of the heavy-duty algorithm design and calibration is projected at 6 years without any major modifications. However, staff did account for minor algorithm and calibration modifications after three years. The cost of the three-year midpoint algorithm and calibration modifications was discounted by 80 percent and 70 percent, respectively. Although staff projects that manufacturers will try to be as cost efficient as possible in developing compliant and robust HDOBD systems, staff realizes that implementing a new program such as HDOBD is challenging and as a result manufacturers may have numerous missteps and inefficiencies in developing their systems especially in the early years of the program. As such, staff applied an additional adjustment factor to both the algorithm development and calibration costs to account for inefficiencies such as algorithm or calibration mistakes that require reworks, new staff learning curves, etc. The inefficiency factor was set at two and therefore effectively doubles staff's cost estimates for algorithm development and calibration. Details of the research costs are located in the Appendix and are summarized in Table II-3.

Engineering Support Costs

The engineering support costs include the labor costs to conduct the certification demonstration tests and production vehicle evaluation tests that are required under the HDOBD regulations. Earlier, staff had defined the hypothetical engine manufacturer's products as consisting of two engine displacements, four engine families per displacement, and five ratings per engine family. Using these assumptions, the number of engines that were allocated each year for testing of verification of standardized requirements was 80 vehicles total. For simplicity, staff assumed the same number of vehicles will be tested in subsequent years even though the actual tested numbers will likely be less since manufacturers are expected to carry over data from previous years for systems identical to previous model year vehicles. For the verification of in-use monitoring performance requirement, staff projects that manufacturers will group its engine families into three OBD groups for certification. Within these OBD groups, staff assumed that there would be an average of three vehicle usage applications (e.g., line-haul trucks, buses, medium-sized local delivery vehicles or vocational vehicles) per

OBD group and a required sample size of 15 vehicles per usage application per OBD group. Therefore, the number of vehicles that staff allocated for the verification of in-use monitoring performance requirement was 135 vehicles. For the certification demonstration testing, two engines were used for estimating the certification demonstration testing costs. For verification of monitoring requirements, two engines and two vehicles were used for estimating costs. Details of the engineering support cost analysis are available in the Appendix and are summarized in Table II-3.

Legal and Administrative Costs

The additional hardware to be used on heavy-duty OBD vehicles is not expected to introduce increased liability issues. However, during the phase-in of heavy-duty OBD diagnostics, the staff believes that legal costs to study possible patent infringement of diagnostic methods may be required. Acknowledging this situation, the staff assumed one additional legal staff allotting one-quarter of his/her time to patent research would be required over a three-year period. Finally, additional administration costs were included in the analysis to address the additional certification information requirements of the regulation. Based upon the administrative staff allocation for light-duty vehicle and medium-duty vehicle manufacturers with similar certification requirements, the staff has allocated one additional engineer to conduct certification administrative duties. The legal and administrative costs are summarized in Tables II-3.

Investment Recovery Costs – Equipment and Machinery

This portion of the cost analysis includes accounting for machinery and equipment to manufacture the part, assembly plant changes, vehicle development, and cost of capital recovery. Since virtually all heavy-duty OBD parts are expected to be acquired from suppliers, these costs were included in the price of the part purchased from the supplier. Although there are additional sensors (four additional sensors for the 2016 SCR-based system used in this analysis) that are required for HDOBD, staff believes the assembly changes needed to accommodate the installation of these additional sensors will be very small and therefore no additional costs were ascribed for this category of the analysis. Vehicle development costs include the cost of developing limit parts, breakout boxes, and other equipment that are needed for vehicle development, calibration, and certification demonstration testing. Vehicle development costs also include testing costs (excluding labor costs) and is equivalent to the cost of contracting out for testing. The testing costs were estimated based upon information provided by outside test laboratories and engine manufacturers. The investment recovery costs are summarized in Table II-4.

Capital Recovery Costs

The cost of capital recovery (return on investment) was calculated at six percent of the total costs to the engine manufacturer. These costs are shown in Table II-4.

Vehicle Manufacturer Costs

Since the price of engines will increase due to the heavy-duty OBD regulation, it is appropriate to account for the additional interest that the vehicle manufacturer will pay for financing the cost of the engine. An interest rate of six percent was assumed on the incremental cost, and, on average, engines were assumed to remain in the manufacturer's inventory for three months until the truck/coach is completed and sold. These costs are shown in Table II-4.

<u>Tables for Diesel Engine Cost Analysis</u>

Table II-1: Incremental cost of Heavy-Duty Diesel Engines OBD System

Emission Control Technology (a)	Tech. cost est. (in dollars)	% HDDE that will req. tech. for control	counted in EPA 2010 standards or earlier	% HDDE that will req. tech. only for OBD	% HDDE that will req. tech. for 2010+OBD	Inc. cost only OBD (dollars)	Revised Inc. cost 2010+OBD (dollars)
Increased ECU capability memory	5.00	0	no	100	100	5.00	5.00
Fuel system pressure sensor	25.00	100	yes	0	0	0.00	0.00
MAF sensor for EGR control	22.50	85	no	0	85	0.00	19.13
A/F sensor for EGR trim/control	15.00	35	no	0	35	0.00	5.25
Temp sensor for EGR cooler monitor	5.00	0	no	65	65	3.25	3.25
A/F sensor for injection quantity monitor	15.00	0	no	15	15	2.25	2.25
Boost pressure sensor	10.00	100	yes	0	0	0.00	0.00
Charge air cooler temperature sensor	5.00	100	yes	0	0	0.00	0.00
Exhaust temperature sensor engine out/oxy cat inlet	10.00	100	no	0	100	0.00	10.00
Exhaust temperature sensor PM filter inlet/oxy cat outlet	10.00	100	no	0	100	0.00	10.00
Dual A/F sensors for NOx adsorber	30.00	20	no	0	20	0.00	-14.00
Exhaust temperature sensor NOx adsorber inlet	10.00	20	yes	0	0	0.00	0.00
Exhaust temperature sensor SCR inlet	10.00	80	yes	0	0	0.00	0.00
NOx sensor for SCR	75.00	80	no	0	80	0.00	-18.75
Differential pressure sensor for PM filter	45.00	100	yes	0	0	0.00	0.00
PCV hardware change to meet design requirements	2.50	0	no	100	100	2.50	2.50
Glow plug/intake air heater current measurement	50.00	0	no	10	10	5.00	5.00
MIL circuit monitor hardware	7.50	0	no	100	100	7.50	7.50
Wait to start lamp circuit hardware	0.50	0	no	10	10	0.05	0.05
Total incremental component cost						15.05	37.18

(a) Manufacturers are projected to utilize an oxidation catalyst, PM trap, and either a lean NOx trap or SCR catalyst.

Tables II-2

Incremental assembly costs for Heavy-Duty Diesel Engines

Assembly operation	Cost (dollars)	% of HDDEs that req. assem. op.	Inc. cost (dollars)
Installing flanges for MAF sensor for EGR control	0.40	85	0.34
Installing A/F sensor boss for EGR trim/control	0.10	35	0.04
Installing Temp. sensor boss for EGR cooler monitor	0.10	65	0.07
Installing A/F sensor boss for injection quantity monitor	0.10	15	0.02
Installing Exhaust temp. sensor boss (engine out/oxy cat inlet)	0.10	100	0.10
Installing Exhaust temp. sensor boss (PM filter inlet/oxy cat outlet)	0.10	100	0.10
Installing Dual A/F sensor bosses for NOx adsorber	0.20	20	0.02
Total Incremental Assem. Cost			0.68

Note: These are the costs to install the bosses and flanges for the sensors. We have not added the costs to install the sensors themselves

Incremental warranty costs for Heavy-Duty Diesel Engines

Warranted Part	Cost of Part (a) (dollars)	Cost of Labor (b)(c) (dollars)	% of HDDEs that req. tech only for OBD	% of HDDEs that req. tech for OBD + 2010 (d)	warranty rate%	OBD only Warranty Cost (dollars)	2010 + OBD Warranty Cost (e) (dollars)
MAF sensor for EGR control	27.00	32.5	0	85	0.5	0.00	0.25
A/F sensor for EGR trim/control	18.00	32.5	0	35	1	0.00	0.18
Temp sensor for EGR cooler monitor	6.00	32.5	65	65	0.1	0.03	0.03
A/F sensor for injection quantity monitor	18.00	32.5	15	15	1	0.08	0.08
Exhaust temperature sensor engine out/oxy cat inlet	12.00	32.5	0	100	0.2	0.00	0.09
Exhaust temperature sensor PM filter inlet/oxy cat outlet	12.00	32.5	0	100	0.2	0.00	0.09
Dual A/F sensors for NOx adsorber	36.00	65	0	20	0.5	0.00	-0.05
NOx sensor for SCR	90.00	32.5	0	80	1	0.00	0.98
Glow plug/intake air heater current measurement	60.00	32.5	10	10	0.05	0.00	0.00
Total Incremental Warranty Cost						0.11	1.64

(a) Assume cost of parts are higher for warranted parts than production parts due to packaging, distribution to dealers and smaller orders.
(b) Total diagnostic and repair time for replacing one sensor is estimated at 30 minutes.
(c) Labor rate is $65/hour. The labor costs include diagnostic and repair time.
(d) Incremental usage above original EPA 2010 standards hardware usage estimate.
(e) Incremental cost above original EPA 2010 standards hardware cost estimate.

Incremental shipping costs for Heavy-Duty Diesel Engines

Shipped Part	Cost of Shipping (dollars)
MAF sensor for EGR control	0.26
A/F sensor for EGR trim/control	0.11
Temp sensor for EGR cooler monitor	0.20
A/F sensor for injection quantity monitor	0.05
Exhaust temperature sensor engine out/oxy cat inlet	0.30
Exhaust temperature sensor PM filter inlet/oxy cat outlet	0.30
Dual A/F sensors for NOx adsorber	0.00
Total Incremental Shipping Costs	1.20

Tables II-3: Support Costs

(A) Development and Calibration Cost of Heavy-Duty Diesel OBD Technology (Research)

Staff	Number of Staff	Staff Cost (a)	Testing Costs (b)	Equipment and Limit Parts	Cost/vehicle(c)
	(person yrs.)	(in dollars)	(in dollars)	(in dollars)	(dollars/veh.)
	0	0	23,402,785	1,000	54.18
Engineer	75.73	9,713,866	0	0	22.49
			Total		76.66

(B) DDV and PVE Testing Cost of Heavy-Duty Diesel OBD (Engineering Support)

Staff	Number of Staff	Staff Cost (a)	Testing and Equipment Costs (d)	Cost/vehicle(c)
	(person yrs.)	(in dollars)	(in dollars)	(dollars/veh.)
	0	0	0	0.00
Test Cell Technician	0.60	59,980	156,038	0.50
			Total	0.50

(C) Legal and Administrative costs

	No. of Staff required	Number of years	Staff cost (in dollars)	Cost/vehicle (c) (dollars/vehicle)
Legal	0.25	3	150,000	0.35
Administrative	1	6	900,000	2.08
			Total	2.43

(a) Development cost includes personnel, overhead and other miscellaneous costs at a total rate of $150k/yr for an engineer and $100k/yr for a technician.
(b) Testing Costs includes Labor Costs for Technicians needed to staff the Tests
(c) Staff cost has been distributed over 72,000 diesel engines per year for a total of 6 years.
(d) Equipment costs have been distributed over 72,000 diesel engines per year for a total of 6 years

Table II-4: Incremental Consumer Cost of Heavy-Duty Diesel Vehicle OBD System

		HDDV (in dollars)
Variable costs	Component Assembly Warranty Shipping	37.18 0.68 1.64 1.20
Support costs	Research Engineering Support Legal Administrative	22.49 0.14 0.35 2.08
Investment recovery costs	Mach. & equipment Assembly plant changes Development/Testing	0.00 0.00 54.54
Capital recovery (a)		7.22
Truck/Coach Builder costs	Cost of capital recovery (b)	1.87
Total cost		129.37

(a) Cost of capital recovery was calculated at 6% of the total incremental costs.
(b) Cost of capital recovery was calculated at 6%. Engines are assumed to remain in inventory for 3 months.

Gasoline Engine Cost Analysis

The gasoline engine cost analysis utilized a similar methodology as the diesel engine cost analysis. Currently there are only two heavy-duty gasoline engine manufacturers. These manufacturers produce a full line of gasoline engines ranging from light-duty engines to heavy-duty engines. Based upon these manufacturers current products, we have assumed the average gasoline engine manufacturer will produce two engine families for a total production of 16,000 engines per year. Results of the analysis indicate the learned-out costs per engine to incorporate the proposed heavy-duty OBD regulation on gasoline engines would be $35.04. Details of the analysis are described below.

Cost of Additional Hardware

Current heavy-duty gasoline engines are essentially equivalent to manufacturers medium-duty engines with minor modifications. These medium-duty engines are certified to OBD II requirements that, at a minimum, are as stringent as the HDOBD proposal. Therefore, staff projects that similar technologies will be used to comply with the HDOBD regulations. As such, the only additional sensors and hardware that are projected to be required for complying with the HDOBD requirements are an O2 sensor for monitoring the catalyst and all of the necessary hardware to comply with the evaporative system monitoring requirements (e.g., vent valve, pressure sensor, wires, keep alive-memory, etc.). The cost of the additional hardware is presented in Table II-5.

Cost of Assembly

Other variable costs include costs of assembly, shipping, and warranty. Costs to assemble OBD systems for heavy-duty gasoline engines are not expected to be much different than those for engines without OBD systems. The additional assembly costs for the majority of engines are installation of an O2 sensor boss for the catalyst monitor, pressure sensor boss for the evaporative system monitor, and vent valve flanges for the evaporative system monitor. These costs are presented in Table II-5.

Cost of Shipping and Warranty

Shipping costs for heavy-duty OBD engines are projected to be nearly the same as non-OBD engines. This is because only an O2 sensor, vent valve, and a pressure sensor would be added to the engine assembly. The cost of shipping the various sensors was estimated to add $0.60 each to the cost of the system (assuming that sensors will be shipped in bulk to the manufacturer). Warranty costs are also projected to be minimal since many of these parts have been included in light- and medium-duty vehicles since 1996 and have proven low warranty rates. The shipping and warranty costs are summarized in Table II-5.

Research Costs

As discussed earlier, research costs include the engineering and other labor costs (e.g., technicians) needed to develop and calibrate the base heavy-duty OBD algorithms. Since these engines are derived from medium-duty engines that already include monitors required for HDOBD, staff did not allocate any costs to develop the base HDOBD algorithms. Costs were only allocated to calibrate the evaporative system monitor. The research costs are presented in Table II-5.

Other Costs

No additional costs were allocated for engineering support, legal, and administrative costs since these are projected to be small. Investment recovery costs, capital recovery costs, and vehicle manufacturer costs were conducted similar to the diesel engine cost analysis and are presented in Tables II-5 and II-6.

Tables for Gasoline Engine Cost Analysis

Tables II-5:

Incremental cost of Heavy-Duty Gasoline Engines OBD System

Emission Control Technology	Tech. cost est. (in dollars)	% HDGE that will req. tech. for control	counted in EPA 2010 standards or earlier	% HDE that will req. tech. only for OBD	% HDE that will req. tech. for 2010+ OBD	Inc. cost only OBD (dollars)	Revised Inc. cost 2010+ OBD (dollars)
Rear O2 Sensor	10.00	0	no	100	100	$10.00	$10.00
Evap system hardware (vent valve, pressure sensor, wiring, keep-alive memory	20.00	0	no	100	100	$20.00	$20.00
Total incremental component cost						$30.00	$30.00

Incremental assembly costs for Heavy-Duty Gasoline Engines

Assembly operation	Cost (dollars)	% of HDGEs that req. assem. op.	Inc. cost (dollars)
Installing O2 sensor boss for oxidation catalyst monitoring	0.10	100	0.10
Installing pressure sensor boss for evaporative system monitor	0.10	100	0.10
Installing flanges for vent valve for evaporative system monitor	0.40	100	0.40
Total Incremental Assem. Cost			0.20

These are the costs to install the bosses and flanges for the sensors. We have not added the costs to install the sensors themselves.

Incremental warranty costs for Heavy-Duty Gasoline Engines

Warranted Part	Cost of Part (a) (dollars)	Cost of Labor (b)(c) (dollars)	% of HDDEs that req. tech. only for OBD	% of HDDEs that req tech for OBD + 2010 (d)	warranty rate%	OBD only Warranty Cost (dollars)	2010 + OBD Warranty Cost (e) (dollars)
O2 sensor for oxy cat monitor	0.48	32.5	100	100	0.1	0.03	0.03
Evap system hardware (vent valve, pressure sensor, wiring, keep-alive memory	0.00	32.5	100	100	0.1	0.03	0.03
Total Incremental Warranty Cost						0.07	0.07

(a) Assume cost of parts are higher for warranted parts than production parts due to packaging, distribution to dealers and smaller orders.
(b) Total diagnostic and repair time for replacing one sensor is estimated at 30 minutes.
(c) Labor rate is $65/hour. The labor costs include diagnostic and repair time.
(d) Incremental usage above original EPA 2010 standards hardware usage estimate.
(e) Incremental cost above original EPA 2010 standards hardware cost estimate.

Incremental shipping costs for Heavy-Duty Gasoline Engines

Shipped Part	Cost of shipping (dollars)
O2 sensor for oxy cat monitor	0.30
Evap system hardware (vent valve, pressure sensor, wiring, keep-alive memory)	0.30
Total Incremental Shipping Costs	0.60

Development and Calibration Cost of Heavy-Duty Gasoline OBD Technology (Research)

Staff	Number of Staff (person yrs.)	Staff Cost (a) (in dollars)	Testing Costs (b) (in dollars)	Equipment and Limit Parts (in dollars)	Cost/vehicle(c) (dollars/veh.)
	0	0	84,630	2,000	0.96
Engineer	0.56	$67,200	0	0	0.75
			Total		1.71

(a) Development cost includes personnel, overhead and other miscellaneous costs at a total rate of $150k/yr for an engineer and $100k/yr for a technician.
(b) Testing Costs includes Labor Costs for Technicians needed to staff the Tests
(c) Staff cost has been distributed over 15000 gasoline engines per year for a total of 6 years.
(d) Equipment costs have been distributed over 15000 gasoline engines per year for a total of 6 years

Table II-6: Incremental Consumer Cost of Heavy-Duty Gasoline Vehicle OBD System

		HDGV (in dollars)
Variable costs	Component	30.00
	Assembly	0.20
	Warranty	0.07
	Shipping	0.60
Support costs	Research	0.75
	Engineering Support	0.00
	Legal	0.00
	Administrative	0.00
Investment recovery costs	Mach. & equipment	0.00
	Assembly plant changes	0.00
	Development/Testing	0.96
Capital recovery (a)		1.95
Truck/Coach Builder costs	Cost of capital recovery (b)	0.51
Total cost		35.04

(a) Cost of capital recovery was calculated at 6% of the total incremental costs.
(b) Cost of capital recovery was calculated at 6%. Engines are assumed to remain in inventory for 3 months.

B. Repair Costs

Because the primary estimated emission benefits calculated for the OBD system are from the identification and subsequent repair of vehicles with malfunctions, staff estimated the costs to vehicle owners or operators to perform those repairs. Using the same categories that were used in EMFAC for component failures, staff calculated the number of repairs for each category that were performed as a result of the 30 percent repair rate assumed for OBD. Additionally for each category, staff calculated an average repair cost. The repair cost was estimated from data from manufacturers, suppliers, and, where applicable, light- and medium-duty repair data.

Specifically, staff estimated different repair costs for three of the categories. For PM filter leaks, it was estimated that the only likely repair in that category was replacement of the PM filter for a cost to the vehicle owner of $4500. For the category of PM filter disabled, however, zero repair cost was assigned because this category largely represents a tampering rate and the OBD program should not bear the cost of individual owners who have chosen to illegally take their vehicle out of compliance by tampering the system and then are forced to bring it back into compliance by an inspection program. For the NOx aftertreatment category, a range of repair costs were analyzed for the various failures such as $200 for in-exhaust injector replacement or reductant delivery component repair up to $3,000 for replacement of the SCR catalyst substrate (or adsorber) itself. For this category, an average repair cost of $1,000 was assumed.

For all other repairs (sensors, wiring, fuel system, etc.), an average repair cost of $450 was used. This number was derived primarily from light-duty OBD II repair studies and is appropriate because the remainder of the components are similar in cost and labor to repair. The $450 number is calculated from a U.S. EPA study of high mileage vehicle repair costs to extinguish the MIL. The study found, with a 95 percent confidence interval, that the average repair cost was between $343 and $563. These numbers were slightly higher than what an earlier U.S. EPA study had found for the average repair costs to correct I/M 240 failures (between $217- $416 with a 95 percent confidence interval). It should be noted that these light-duty repair costs include OBD II detected powertrain repairs outside of the engine such as transmission repairs which are typically much more expensive than engine repairs and drive the cost higher. Further, these OBD II repair costs also used only OEM catalysts (ranging from $600-$1200 in repair cost), which likely cost at least as much as the oxidation catalysts used on diesel engines and account for a larger portion of the repairs. Thus, even though some individual components on a diesel engine may cost more than the corresponding component on a light-duty engine (e.g., diesel fuel injectors versus gasoline fuel injectors), the $450 number also includes many repairs of components on the gasoline side that are more expensive than the corresponding diesel side and is thus a reasonable estimate. For the majority of components in these categories such as sensors, the parts costs are expected to be nearly identical to light-duty engines. Labor rates (hourly rates and labor hours per repair) for heavy-duty technicians are also very similar to light-duty.

The incremental fraction of repairs caused by OBD for each category was calculated and multiplied by the applicable repair cost for that category. For this analysis, it was calculated that OBD resulted in an additional 0.67 repairs per engine over its life with an incremental repair cost of $496 per engine for the 0.67 repairs. (For comparison, this translates to a cost of $741 per repair for a heavy-duty engine as opposed to the $450 per repair number found in light-duty).

C. Cost Effectiveness of the Proposed Requirements

Based on the emission benefit analysis and the cost numbers identified above, the cost effectiveness of the OBD regulation was calculated. For the calculation, it was assumed that half of the cost was for PM emission benefit and the other half was for ROG+NOx benefit. Accordingly, the per engine cost to implement OBD ($132) was added to the per engine repair cost ($496) for a total cost of $628 per engine. Splitting that in half, $314 was attributed to PM benefit for a cost-effectiveness of $13.08 per pound of PM. The other half of the cost was attributed to ROG+NOx benefit for a cost-effectiveness of $0.05 per pound of ROG+NOx. Both values compare favorably with the cost-effectiveness of other, recently adopted regulations.

XV. ECONOMIC IMPACT ANALYSIS

Overall, the proposed regulation is expected to have a negligible impact on the profitability of heavy-duty engine manufacturers. It is anticipated that the proposed regulation would result in negligible costs to vehicle manufacturers. Staff believes, therefore, that the proposed requirements would cause no noticeable adverse impact in California employment, business status, and competitiveness.

A. Legal requirements

Sections 11346.3 of the Government Code requires State agencies to assess the potential for adverse economic impacts on California business enterprises and individuals when proposing to adopt or amend any administrative regulation. Section 43101 of the Health and Safety Code similarly requires that the Board consider the impact of adopted standards on the California economy. This assessment shall include a consideration of the impact of the proposed regulation on California jobs, business expansion, elimination, or creation, and the ability of California business to compete.

In addition, state agencies are required to estimate the cost or savings to any state or local agency, and school districts. The estimate is to include any non-discretionary cost or savings to local agencies and the cost or savings in federal funding to the state.

B. Affected businesses and potential impacts

Any business involved in manufacturing, purchasing, or servicing heavy-duty engines and vehicles could be affected by the proposed regulation. There are 21 engine manufacturers, none of which are located in California. Of these businesses, two of the engine manufacturing companies are assumed to be “small businesses” (i.e., selling less than 150 engines per year based on California certification data).

There are approximately 8 major vehicle manufacturers, but staff has been unable to obtain an estimation of the total number of vehicle manufacturers that manufacture and sell heavy-duty vehicles in California. Thus, staff is unable to determine how many of these companies are located in California and how many are considered “small businesses.” However, the cost related to vehicle manufacturers is assumed to be negligible.

C. Potential impacts on vehicle operators

The proposed regulation would provide OBD information and encourage manufacturers to build more durable engines, which would result in the need for fewer repairs and savings for vehicle owners. However, OBD is expected to detect malfunctions that may otherwise have gone undetected (and thus, unrepaired) by the vehicle owner. A single additional repair was estimated to occur on approximately two-thirds of the trucks over a 21 year lifetime as a result of OBD at an average cost of $741 per repair. This is a conservative cost estimate, since OBD will potentially result in savings by catching problems early before they adversely affect other components and systems in the engine. The proposed OBD regulation is anticipated to have a negligible impact on new vehicle prices, since the calculated increase in retail price of an engine to meet OBD is less than one percent of the retail cost of the engine and less than 0.2 percent of the retail cost of a heavy-duty vehicle.

D. Potential impacts on business competitiveness

The proposed regulation is not expected to adversely impact the ability of California businesses to compete with businesses in other states as the proposed standards are anticipated to have only a negligible impact on retail prices of new engines and vehicles. Additionally, U.S. EPA is expected to adopt federal heavy-duty OBD requirements that are harmonized with those of ARB. Therefore, any increase in costs will also be experienced by non-California businesses due to federal requirements. Thus, any price increases of heavy-duty vehicles are not expected to dampen the demand for heavy-duty trucks in California relative to other states, since price increases would be the same nationwide.

Further, all manufacturers that manufacture heavy-duty engines for sale in California are subject to the proposed heavy-duty OBD requirements regardless of where they are located and where the engines are planned for sale. As stated above, none of the heavy-duty engine manufacturers are located in California.

E. Potential impact on employment

The proposed regulation is not expected to cause a noticeable change in California employment because California accounts for only a small share of engine manufacturing employment, and the minimal additional work done by vehicle manufacturers can be done with existing staff.

However, some jobs may be created at heavy-duty engine manufacturing companies. Currently, heavy-duty engine manufacturers lack significant experience in designing and implementing OBD systems on heavy-duty engine. This may result in additional jobs for programmers and engineers.

F. Potential impact on business creation, elimination, or expansion

The proposed regulation is not expected to affect business creation, elimination, or expansion.

XVI. ISSUES OF CONTROVERSY

A. Industry believes the proposed HD OBD emission thresholds at which a component or system would be considered malfunctioning are too low. They maintain it is not technically feasible to reliably evaluate the performance of some components or systems at the level of deterioration required by the proposed emission thresholds.

It should be noted that OBD systems do not directly measure emissions using some sort of sensor in the tailpipe. Rather, manufacturers use an indirect method to estimate emission increases. They progressively deteriorate emission control components and emission test them on an engine in a laboratory one at a time to correlate reduced performance with emission increases. By using an OBD system to monitor all of the emission related components on an engine for deterioration during on road driving, malfunctions can be detected when emissions are projected to increase above prescribed thresholds based on the prior testing.

ARB staff has carefully considered the feasibility of reliably determining when a malfunction is present at the emission thresholds being proposed in the regulation. Whenever feasible, our goal is to detect a malfunctioning component or system when it has significantly deteriorated or failed such that emissions are projected to exceed applicable standards by about 50 percent. Allowing a larger increase in emissions before signaling a malfunction would undermine the benefits of setting stringent tailpipe emission standards in the first place. Even with the goal of maintaining emissions near the standards, however, staff is proposing one threshold that exceeds the emission standards by up to 400 percent in recognition of technical constraints in detecting deterioration or failures at lower levels. Industry is proposing thresholds that significantly exceed those staff is proposing.

Staff has identified approaches that could be used to reliably detect component malfunctions at the proposed thresholds. They are based on input from engineering consultants, technical papers and strategies for similar monitors that have already been adopted for vehicles meeting the OBD II requirements for light and medium-duty vehicles. From a legal standpoint, the hurdle ARB staff must meet to establish “technical feasibility” is to identify monitoring strategies that would enable manufacturers to meet the proposed monitoring thresholds and address criticisms or counter arguments from industry concerning the suggested approaches. ARB staff is not required to assemble hardware or conduct laboratory testing to determine that a monitoring approach being proposed is technically feasible. Some of the emission threshold requirements ARB staff is proposing are considered “technology forcing” in that industry would be expected to pursue the approaches suggested by ARB staff or others and work aggressively to meet them in the timeframe between adoption of the regulation and its required implementation. It is the judgment of ARB staff that industry has not pursued some of the potential approaches sufficiently at this time to conclude that they would not be successful in meeting the thresholds being proposed. Industry’s proposals are based on their current capability with little consideration of future progress that may be possible in improving their monitoring capability.

Some of the emission thresholds being proposed require detecting a malfunction when tailpipe emissions exceed the standards by 50 percent, which is the same increase generally allowed for medium duty diesel vehicles currently meeting the OBD II requirements. This threshold would apply to monitoring the fuel system, exhaust gas recirculation system, boost control system and other engine systems, many of which are feedback controlled (this means the systems can self-correct for deterioration up to a point). Staff expects the limits of self-correction or other parameters available in heavy duty engine systems are very similar to those used currently in medium duty vehicles meeting the OBD II requirements for reliably determining that a malfunction is present. Use of the 50 percent increase in emissions criterion is applied generally to those components and systems that can affect engine-out emissions. This is in contrast to other generally higher emission threshold criteria applicable to aftertreatment devices that further clean up engine-out emissions to meet the 2007-2010 tailpipe HD emission standards. Really, malfunctions in the devices that increase engine out emissions are easier to detect than the 50 percent emission increase criterion would suggest. This is because engine out emission increases are much higher than 50 percent since the aftertreatment in most of the 2010 engines will significantly further reduce engine out emissions to arrive at a 50 percent emission increase at the tailpipe.

Industry also cites their current level of emission measurement capability as another impediment to being assured they can meet a 50 percent increase in emissions threshold. They claim that measurement variability is greater than the 50 percent increase in emissions staff is allowing before detecting a malfunction. However, staff is not convinced based on the emission variability data industry has presented that this will be a real constraint to meeting the proposed threshold. Staff also expects that emission measurement capability will continue to improve as has been the case in the past when new, substantially lower emission standards were adopted. Staff is also proposing to forego enforcement actions regarding emission thresholds until emissions are double the thresholds through 2015. Thus, there is considerable time for emission measurement capability to improve before threshold liability becomes a more real concern.

Perhaps the more challenging emission threshold monitors apply to the aftertreatment systems such as detection of a deteriorated particulate filter. Industry has indicated they have been unable to develop a monitoring strategy that would allow them to detect cracks or other breaches in a PM filter before emissions exceed the proposed threshold of 400 percent above the 2010 emission standard and 150 percent above the 2013 standard. However, staff has indicated that through the use of mathematical models to predict the rate of soot accumulation in a particulate filter, combined with statistical evaluations of measured soot build up subsequent to a regeneration event using pressure and temperature measurements, achieving such thresholds would be possible. While some manufacturers have submitted test results showing use of a pressure sensor alone would not be adequate to detect a deteriorated filter at the proposed threshold, staff has not yet seen data reflective of the more sophisticated approach suggested by staff to achieve an earlier determination of a malfunction. Staff expects industry would need to conduct a broader investigation of monitoring strategies, modeling efforts and statistical methods than we have seen at this time in order to meet the proposed requirements.

For NOx aftertreatment devices, staff is proposing a monitoring threshold 150 percent above the 2010 emission standard and 100 percent above the 2013 standard. This is in consideration of the expected resolution of NOx sensors currently being developed for measuring NOx in the exhaust and in consideration of other NOx control approaches that manufacturers might pursue. Unlike virtually all the other OBD monitors that infer tailpipe emissions from some other monitored parameter, for NOx catalysts that are reliant on NOx sensors to meet the 2007-2010 standards, there is a direct reading of tailpipe NOx emissions, making monitoring at the proposed lower threshold more straightforward.

B. Industry has expressed concern that the number of OBD monitors needing calibration to emission thresholds is excessive and exceeds their development resources.

ARB staff initially proposed that all heavy-duty vehicles incorporate comprehensive HD OBD systems by 2010. Industry responded that they did not have sufficient resources to implement these systems across their full product range, citing the daunting task of meeting the 2007-2010 tailpipe standards in the same timeframe. Staff reviewed some detailed resource information from a couple manufacturers and concluded there was some validity in industry’s concern. As a result, staff then proposed OBD be fully implemented on several engine variants in a manufacturer’s product line, and “extrapolated” onto the remainder of the product line. This could be done using engineering judgment rather than performing a detailed emission threshold evaluation for each engine variant in the first few years. Industry continued to voice concerns over resources even with this proposal. Staff then performed its own evaluation of industry resources and concluded that although the proposal should be within their resources, we were willing to reduce full implementation to just one engine rating within one engine family, and allow extrapolation to other engine variants in the one family only. All the other engine families would not be required to implement HD OBD until 2013 and full liability for all engines to meet the emission thresholds would not begin until 2016. This was in exchange for industry agreeing to implement a comprehensive OBD system in one engine family in 2010. The ARB resource study showed this should be readily accomplished with available resources.

Now industry claims they need further concessions in the form of fewer threshold monitors than would be required to implement a fully capable HD OBD system even on the one engine family. In reviewing the basis for the latest request, staff concluded that industry over-counted the number of required threshold monitors and presented cost and resource estimates that were much higher than our own. The staff analysis concluded the resources needed to meet the latest proposal were well within the manufacturers' capabilities.

C. The heavy-duty engine manufacturers do not support the proposed production engine/vehicle evaluation testing requirements requiring manufacturers to test engines as well as complete vehicles. They also object to the number of vehicles that would need to be tested.

Engine manufacturers contend that since they manufacture only engines, they should test only engines, and argue that procuring completed vehicles for the proposed testing requirements would be cumbersome; they also maintain the number of vehicles required to be tested is too high, adding to the manufacturers' cost and resource burdens. The engine manufacturers believe they should not have to test for vehicle-related problems since they are only responsible for the engine. ARB staff believes, however, that testing for engine compliance in complete vehicles is a necessary requirement. If the OBD system does not function properly when the engine is installed in the vehicle, the system is rendered useless to the end users (i.e., vehicle owner/operators, repair technicians and inspectors). Further, the cost and resource burden would not be as significant as manufacturers have suggested.

The proposed production engine/vehicle evaluation testing requirements would require three different types of testing: standardization testing, monitoring requirements testing, and rate-based testing. Standardization testing would require manufacturers to test one vehicle per engine/chassis combination. The test is straightforward and would require little time per vehicle. It involves plugging in a standardized piece of test equipment (most likely a laptop computer with special software that acts like a generic scan tool and records the communications from the vehicle) to a vehicle and generating a report. This testing would help ensure the engine's on-board computer, when installed in a complete vehicle with other computer modules, is able to communicate properly with a generic scan tool. Monitoring requirements testing would involve manufacturers testing one to three engines and one to three vehicles each year depending on the number of engine families certified. It would involve manufacturers implanting a fault one by one in the emission control system and verifying that each related OBD monitor is able to detect the fault. This testing would help ensure that the OBD monitors accomplish what they are designed to do, which is to detect a fault, store the appropriate fault code, and illuminate the MIL. Rate-based testing would require manufacturers to collect in-use performance data from a minimum of 15 vehicles per engine/chassis combination, and would involve plugging in a scan tool to a vehicle and downloading information pertaining to how frequently emission monitors are running in use. Staff experience with light-duty OBD II has shown that all three tests are essential to ensure the OBD system is working as required in-use and is especially imperative in the first few years of OBD introduction. There have been numerous communication problems found in the field, including cases where the scan tools were unable to obtain any information from a vehicle's OBD system, thus significantly hindering repair work and inspection programs. Additionally, OBD monitors have been found to either be unable to detect a malfunction or run much less frequently than desired, which results in less probability of detecting emission-related malfunctions.

Staff experience with light-duty OBD II has also shown that testing needs to be done on vehicles, not just engines. Due to the array of vehicle manufacturers, each of which will likely have little experience or knowledge of OBD systems, it only makes sense for the experienced engine manufacturers to do this testing. Regarding standardization testing, problems with communication could occur during the assembly of the vehicle (e.g., wiring errors, adding computer modules in addition to the engine computer to the network in the vehicle). Additionally, the numerous combinations of engine and chassis increase the likelihood that this problem could occur. This could cause the OBD system to be unable to communicate with a generic scan tool, which would essentially render the OBD system itself useless since no information can be received. Testing of just the engines would not always detect such problems. Regarding monitoring requirements testing, numerous problems have been found in light duty vehicles where monitors did not run as they should, including lack of detection of faults and no illumination of the malfunction indicator light. The manner in which engines run in test cells differs greatly from the manner in which they run in vehicles on the road. Therefore, depending on how the monitor is designed, it may be unable to run in-use in vehicles even though it runs properly as a stand alone engine in a test cell. For perspective, staff estimates that for a manufacturer to conduct all the verification testing being proposed, less than one person year would be required at an additional cost per engine of 50 cents.

D. Similar to the above concern, industry disagrees with the staff proposal requiring manufacturers to test a few vehicles per year to demonstrate compliance with HD OBD emission thresholds for the major monitors.

To conserve resources, staff is proposing that engine manufacturers be required to calibrate only a few engines to the OBD thresholds using the official certification test procedure. All other engines in the manufacturer’s product lineup could be calibrated using an “extrapolation” process where engineering judgment and minimal testing is relied upon to establish the OBD thresholds. To address the need to be certain the extrapolation process is being carried out properly, however, staff is proposing that manufacturers implant faults in up to three engines per year and run emission tests to demonstrate the malfunction light is illuminated. Given that in-use compliance testing using the official certification test procedure will be expensive due to the need to remove engines from vehicles, staff expects such testing to be performed infrequently in use. As a result, staff needs some additional assurance from the manufacturers that the multiple engine variants in its product line have been properly calibrated to the OBD thresholds. This demonstration testing would only require limited resources each year and would provide much more certainty of compliance. Industry has expressed concern about the ongoing resources needed to perform the testing and the potential liability should problems eventually be found.

E. Industry objects to the proposed requirement to report whether engine operation at any given time is in a region for which they are liable to meet in-use emission testing limits.

In order to test heavy duty engines for compliance with applicable emission standards in-use, the usual procedure has been to remove the engines from the vehicles. They would then be tested separately according to prescribed regulatory test cycles using a stationary engine dynamometer. Because removal and testing is very expensive and time consuming, ARB recently adopted regulations requiring industry to meet alternate in-use emission limits known as Not-to-Exceed (NTE) emission limits. This NTE concept allows the vehicles to be tested "on the road", without removal of the engine, using a portable emission measurement system (PEMS). The NTE limits are numerically less stringent than the official certification test protocol standards to allow for diverse environmental conditions and varying vehicle driveline configurations which may affect emissions. In addition, manufacturers are permitted to briefly deactivate emission systems under limited but permissible operating conditions approved by the ARB staff on a case by case basis such as when engine coolant temperatures are excessive, humidity conditions reach extremes, or to prevent engine damage under some conditions. One of the difficulties with conducting vehicle-based testing is that it is often difficult to determine when the engine is operating in a zone that permits emission controls to be deactivated temporarily. When an engine is operating in a deactivation zone, the emission data for that moment must be excluded from the test results in determining compliance with the NTE emission limits. To make these determinations, it would be necessary to post-process huge amounts of data to arrive at an overall emission test result. Such post processing could introduce errors and affect the validity of many of the tests. Therefore, since the engine computer controls the engine in accordance with the permitted deactivation criteria, it can also easily track when it is operating in such a condition. Therefore, it would facilitate testing to have the engine OBD system report whether it is operating either in or out of a zone where emission measurements would be valid to count.

The engine manufacturers have complained that such requirements should not take place in a HD OBD regulation; rather they should be addressed in rulemakings concerning in-use PEMS testing. But ARB staff considers this regulation the proper venue to address these requirements since they can easily be incorporated into the HD OBD system and output in a standardized manner through the OBD connector. As long as staff has properly noticed the subject, we believe we have the authority to address these requirements in this rulemaking. The engine manufacturers also cite confidentiality concerns about their operating strategies, suggesting their competitors may more easily reverse engineer their emission and fuel economy strategies if they can determine when the engines are operating in a zone where emission controls may be temporarily deactivated. However, with the vast number of variables that are inputs to the engine control system at any given moment, staff believes such information would be of little value in any potential effort to reverse engineer an engine manufacturer's control strategy.

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Below is a list of documents and other information that the ARB staff relied upon in proposing the heavy-duty OBD regulation.

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APPENDIX I

The following tables were used to support the conclusions made in section XIII. "Analysis of Environmental Impacts and Environmental Justice Issues" of the Staff Report.

Estimated Failure Rates for Added EMFAC Categories

2010 Without OBD

Odometer	Cumm Mileage	% Useful		Sensor 1	Sensor 2	DPF Leak	NOx aftertreatment
80705	80705	8%		0	0	0	0
85152	165857	8%		0	0	0	0
86460	252317	9%		35	0	0	0
85386	337703	8%		60	0	0	0
82571	420274	8%		90	0	5.8	0
78547	498821	8%		90	0	9.7	10.0
73755	572576	7%		90	0	13.5	15.7
68546	641122	7%		90	5	17.1	21.0
63199	704321	6%		90	5	20.5	25.9
57926	762247	6%		90	5	23.6	30.3
52881	815128	5%		90	5	26.5	34.4
48169	863297	5%		90	5	29.1	38.1
43854	907151	4%		90	5	31.5	41.5
39965	947116	4%		90	5	33.8	44.6
36504	983620	4%		90	5	35.8	47.4
33452	**1E+06**	3%		90	5	37.6	50.0
		100%					
Fail Rate				68.13	2.19	13.93	17.14

Assumptions:
Sensor 1 and Sensor 2 are the same sensor (e.g., post SCR NOx sensor) and represent first fail in life and second fail in life.
Without OBD, very few of first sensor failures get fixed so minimal chance for second failure to occur.
Absent OBD, not much motivation to fix sensor failure, DPF leak, or NOx aftertreatment (no loss of engine performance plus likely increase in fuel economy/SCR reductant savings).

2010 With OBD

Odometer	Cumm Mileage	% Useful		Sensor 1	Sensor 2	DPF Leak	NOx aftertreatment
80705	80705	8%		0.0	0.0	0.0	0.0
85152	165857	8%		0.0	0.0	0.0	0.0
86460	252317	9%		24.5	0.0	0.0	0.0
85386	337703	8%		42.0	0.0	0.0	0.0
82571	420274	8%		63.0	0.0	4.1	0.0
78547	498821	8%		63.0	0.0	6.8	7.0
73755	572576	7%		63.0	0.0	9.4	11.0
68546	641122	7%		63.0	5.0	12.0	14.7
63199	704321	6%		63.0	8.0	14.3	18.1
57926	762247	6%		63.0	10.0	16.5	21.2
52881	815128	5%		63.0	10.0	18.5	24.1
48169	863297	5%		63.0	10.0	20.4	26.7
43854	907151	4%		63.0	10.0	22.1	29.1
39965	947116	4%		63.0	10.0	23.6	31.2
36504	983620	4%		63.0	10.0	25.0	33.2
33452	**1E+06**	3%		63.0	10.0	26.3	35.0
		100%					
Fail Rate				47.69	3.91	9.75	12.00

Assumptions:
Sensor 1 and Sensor 2 are the same sensor (e.g., post SCR NOx sensor) and represent first fail in life and second fail in life.
With OBD, about 1/3 of the MILs on for these four failures get fixed immediately (fixed within 10,000 miles of detection is same as fixed immediately). Motivation for fix includes MIL on and HDVIP/fleets annual self-inspection rules enforcing repairs of MIL on.
With OBD, chance for Sensor 2 failure is higher than without OBD because some of the first failures actually got fixed giving the sensor a chance to fail a second time later in life.

Heavy-Duty Failure Rates

	Probability of Occurance		Repairs Per Engine Over	Average Cost per Repair	Cost times repairs
	NO OBD 2010+	With OBD 2010+	1,000,000 mile lifetime		
Timing Advanced	2	1.33	0.01	$ 450	$ 3.0
Timing Retarded	2	1.33	0.01	$ 450	$ 3.0
Minor Injection Problems	13	8.67	0.04	$ 450	$ 19.5
NOx Aftertreatment Sensor #1	68	47.69	0.20	$ 450	$ 92.0
NOx Aftertreatment Sensor #2	2.2	3.91	-0.02	$ 450	$ (7.7)
PM Filter leak	14	9.75	0.04	$ 4,500	$ 188.1
PM Filter Disabled	2	1.33	0.01	$ -	$ -
Fuel Pressure High	0	0.00	0.00	$ 450	$ -
Clogged Air Filter	15	10.00	0.05	$ 450	$ 22.5
Wrong/Worn Turbo	5	3.33	0.02	$ 450	$ 7.5
Intercooler Clogged	5	3.33	0.02	$ 450	$ 7.5
Other Air Problems	8	5.33	0.03	$ 450	$ 12.0
Engine Failure	2	1.33	0.01	$ 450	$ 3.0
Excess Oil Consumption	3	2.00	0.01	$ 450	$ 4.5
Electronics Failure	30	20.00	0.10	$ 450	$ 45.0
Electronics Tampered	5	3.33	0.02	$ 450	$ 7.5
Oxy Cat Malfunction	5	3.33	0.02	$ 450	$ 7.5
NOx Aftertreatment Malfunction	17	12.00	0.05	$ 1,000	$ 51.4
EGR Disabled/Low Flow	20	13.33	0.07	$ 450	$ 30.0
		sum	0.67 repairs per engine caused by OBD		$ 496.2 cost of 0.67 repairs per engine

Heavy-Duty Baseline NO OBD 2010+

Oxides of Nitrogen

Tampered and Mal-maintained
Heavy-Heavy-Duty Trucks

	Oxides of Nitrogen																	
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	8	13	11	5	2	2	70	50	60	60	60	21	0.056	0.065	0.066	0.030	0.012	0.004
Timing Retarded	15	12	9	3	2	2	-20	-20	-20	-20	-20	-7	-0.030	-0.024	-0.018	-0.006	-0.004	-0.001
Minor Injection Problems	20	20	15	15	15	13	-0.5	-5.0	-5.0	-1	-1	-1	-0.001	-0.010	-0.008	-0.002	-0.002	-0.001
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	-5	-5	-5	-1	-1	200	-0.005	-0.005	-0.005	-0.001	-0.001	1.363
NOx Aftertreatment Sensor #2	3	3	3	3	3	2.19	-7	-5	-5	-1	-1	200	-0.002	-0.002	-0.002	0.000	0.000	0.044
PM Filter leak	29	23	16	4	0	13.9	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
PM Filter Disabled	30	23	16	4	0	2	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Pressure High	24	18	13	3	0	0	10	10	10	10	10	2.5	0.024	0.018	0.013	0.003	0.000	0.000
Clogged Air Filter	22	20	15	15	15	15	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	12	10	5	5	5	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	3	7	5	5	5	5	20	20	25	25	25	17.5	0.006	0.014	0.013	0.013	0.013	0.009
Other Air Problems	15	15	8	8	8	8	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	2	-10	-10	-10	-10	-10	-3.5	-0.002	-0.002	-0.002	-0.002	-0.002	-0.001
Excess Oil Consumption	2	2	5	5	3	3	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Failure	0	2	3	3	3	30	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Tampered	0	0	5	5	5	5	0	50	80	80	80	28	0.000	0.000	0.040	0.040	0.040	0.014
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
NOx Aftertreatment Malfunction	0	0	0	0	0	17.1	0	0	0	0	0	300	0.000	0.000	0.000	0.000	0.000	0.514
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	150	0.000	0.000	0.000	0.000	0.000	0.300
													4.6%	5.5%	9.8%	7.6%	5.6%	**395.3%**

Medium-Heavy-Duty Trucks							Oxides of Nitrogen											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	10	10	10	5	2	2	70	50	60	60	60	21	0.070	0.050	0.060	0.030	0.012	0.004
Timing Retarded	6	6	6	3	2	2	-20	-20	-20	-20	-20	-7	-0.012	-0.012	-0.012	-0.006	-0.004	-0.001
Minor Injection Problems	20	20	15	15	15	13	-0.5	-5.0	-5.0	-1	-1	-1	-0.001	-0.010	-0.008	-0.002	-0.002	-0.001
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	-5	-5	-5	-1	-1	200	-0.005	-0.005	-0.005	-0.001	-0.001	1.363
NOx Aftertreatment Sensor #2	3	3	3	3	3	2.19	-7	-5	-5	-1	-1	200	-0.002	-0.002	-0.002	0.000	0.000	0.044
PM Filter leak	18	18	17	4	0	13.9	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
PM Filter Disabled	15	15	14	4	0	2	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Pressure High	14	14	14	3	0	0	10	10	10	10	10	2.5	0.014	0.014	0.014	0.003	0.000	0.000
Clogged Air Filter	23	19	15	15	15	15	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	10	9	5	5	5	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	1	4	5	5	5	5	20	20	25	25	25	17.5	0.002	0.008	0.013	0.013	0.013	0.009
Other Air Problems	14	12	8	8	8	8	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	2	-10	-10	-10	-10	-10	-3.5	-0.002	-0.002	-0.002	-0.002	-0.002	-0.001
Excess Oil Consumption	3	3	5	5	3	3	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Failure	0	0	3	3	3	30	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Tampered	0	0	5	5	5	5	0	50	80	80	80	28	0.000	0.000	0.040	0.040	0.040	0.014
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
NOx Aftertreatment Malfunction	0	0	0	0	2	17.1	0	0	0	0	0	300	0.000	0.000	0.000	0.000	0.000	0.514
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	150	0.000	0.000	0.000	0.000	0.000	0.300
													6.4%	4.2%	10.0%	7.6%	5.6%	**395.3%**

Light-Heavy-Duty Trucks							Oxides of Nitrogen											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	10	10	10	5	2	2	70	50	60	60	60	21	0.070	0.050	0.060	0.030	0.012	0.004
Timing Retarded	10	10	6	3	2	2	-20	-20	-20	-20	-20	-7	-0.020	-0.020	-0.012	-0.006	-0.004	-0.001
Minor Injection Problems	20	20	15	15	15	13	-0.5	-5.0	-5.0	-1	-1	-1	-0.001	-0.010	-0.008	-0.002	-0.002	-0.001
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	-5	-5	-5	-1	-1	200	-0.005	-0.005	-0.005	-0.001	-0.001	1.363
NOx Aftertreatment Sensor #2	5	5	3	3	3	2.19	-7	-5	-5	-1	-1	200	-0.004	-0.003	-0.002	0.000	0.000	0.044
PM Filter leak	2	5	5	4	0	13.9	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
PM Filter Disabled	1	3	3	4	0	2	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Pressure High	15	15	14	3	0	0	10	10	10	10	10	2.5	0.015	0.015	0.014	0.003	0.000	0.000
Clogged Air Filter	21	19	15	15	15	15	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	5	5	5	5	5	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	0	4	5	5	5	5	20	20	25	25	25	17.5	0.000	0.008	0.013	0.013	0.013	0.009
Other Air Problems	9	12	8	8	8	8	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	3	3	2	2	2	2	-10	-10	-10	-10	-10	-3.5	-0.003	-0.003	-0.002	-0.002	-0.002	-0.001
Excess Oil Consumption	5	5	5	5	3	3	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Failure	0	0	3	3	3	30	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Tampered	0	0	5	5	5	5	0	50	80	80	80	28	0.000	0.000	0.040	0.040	0.040	0.014
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
NOx Aftertreatment Malfunction	0	0	0	0	2	17.1	0	0	0	0	0	300	0.000	0.000	0.000	0.000	0.000	0.514
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	150	0.000	0.000	0.000	0.000	0.000	0.300
													5.3%	3.3%	10.0%	7.6%	5.6%	**395.3%**

Hydrocarbons

Heavy-Heavy-Duty Trucks	Hydrocarbons																	
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	8	13	11	5	2	2	0	0	30	30	30	15	0.000	0.000	0.033	0.015	0.006	0.003
Timing Retarded	15	12	9	3	2	2	50	50	50	50	50	25	0.075	0.060	0.045	0.015	0.010	0.005
Minor Injection Problems	20	20	15	15	15	13	7	668	668	1723	1723	862	0.013	1.336	1.002	2.585	2.585	1.120
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	100	668	668	1723	1723	15	0.100	0.668	0.668	1.723	1.723	0.102
NOx Aftertreatment Sensor #2	3	3	3	3	3	2.19	325	668	668	1723	1723	15	0.098	0.200	0.200	0.517	0.517	0.003
PM Filter leak	29	23	16	4	0	13.9	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.014
PM Filter Disabled	30	23	16	4	0	2	-20	-20	0	0	0	10	-0.060	-0.046	0.000	0.000	0.000	0.002
Fuel Pressure High	24	18	13	3	0	0	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.000
Clogged Air Filter	22	20	15	15	15	15	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	12	10	5	5	5	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	3	7	5	5	5	5	-20	-20	-20	-20	-20	-10	-0.006	-0.014	-0.010	-0.010	-0.010	-0.005
Other Air Problems	15	15	8	8	8	8	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	2	200	200	300	500	500	250	0.040	0.040	0.060	0.100	0.100	0.050
Excess Oil Consumption	2	2	5	5	3	3	300	300	300	300	300	150	0.060	0.060	0.150	0.150	0.090	0.045
Electronics Failure	0	2	3	3	3	30	0	30	50	50	50	25	0.000	0.006	0.015	0.015	0.015	0.075
Electronics Tampered	0	0	5	5	5	5	0	0	0	0	0	25	0.000	0.000	0.000	0.000	0.000	0.013
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	100	0	0	50	0.000	0.000	0.063	0.000	0.000	0.025
NOx Aftertreatment Malfunction	0	0	0	0	0	17.1	0	0	40	100	100	15	0.000	0.000	0.000	0.000	0.000	0.026
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
													31.5%	231.3%	248.2%	525.8%	512.4%	182.3%

Medium-Heavy-Duty Trucks							Hydrocarbons											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	10	10	10	5	2	2	0	0	30	30	30	15	0.000	0.000	0.030	0.015	0.006	0.003
Timing Retarded	6	6	6	3	2	2	50	50	50	50	50	25	0.030	0.030	0.030	0.015	0.010	0.005
Minor Injection Problems	20	20	15	15	15	13	7	668	668	1723	1723	862	0.013	1.336	1.002	2.585	2.585	1.120
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	100	668	668	1723	1723	15	0.100	0.668	0.668	1.723	1.723	0.102
NOx Aftertreatment Sensor #2	3	3	3	3	3	2.19	325	668	668	1723	1723	15	0.098	0.200	0.200	0.517	0.517	0.003
PM Filter leak	18	18	17	4	0	13.9	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.014
PM Filter Disabled	15	15	14	4	0	2	-20	-20	0	0	0	10	-0.030	-0.030	0.000	0.000	0.000	0.002
Fuel Pressure High	14	14	14	3	0	0	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.000
Clogged Air Filter	23	19	15	15	15	15	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	10	9	5	5	5	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	1	4	5	5	5	5	-20	-20	-20	-20	-20	-10	-0.002	-0.008	-0.010	-0.010	-0.010	-0.005
Other Air Problems	14	12	8	8	8	8	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	2	200	200	300	500	500	250	0.040	0.040	0.060	0.100	0.100	0.050
Excess Oil Consumption	3	3	5	5	3	3	300	300	300	300	300	150	0.090	0.090	0.150	0.150	0.090	0.045
Electronics Failure	0	0	3	3	3	30	0	30	50	50	50	25	0.000	0.000	0.015	0.015	0.015	0.075
Electronics Tampered	0	0	5	5	5	5	0	0	0	0	0	25	0.000	0.000	0.000	0.000	0.000	0.013
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	100	0	0	50	0.000	0.000	0.060	0.000	0.000	0.025
NOx Aftertreatment Malfunction	0	0	0	0	2	17.1	0	0	40	100	100	15	0.000	0.000	0.000	0.000	0.020	0.026
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
													33.7%	230.8%	242.2%	525.8%	523.3%	182.3%

Light-Heavy-Duty Trucks							Hydrocarbons											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	10	10	10	5	2	2	0	0	30	30	30	15	0.000	0.000	0.030	0.015	0.006	0.003
Timing Retarded	10	10	6	3	2	2	50	50	50	50	50	25	0.050	0.050	0.030	0.015	0.010	0.005
Minor Injection Problems	20	20	15	15	15	13	7	668	668	1723	1723	862	0.013	1.336	1.002	2.585	2.585	1.120
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	100	668	668	1723	1723	15	0.100	0.668	0.668	1.723	1.723	0.102
NOx Aftertreatment Sensor #2	5	5	3	3	3	2.19	325	668	668	1723	1723	15	0.163	0.334	0.200	0.517	0.517	0.003
PM Filter leak	2	5	5	4	0	13.9	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.014
PM Filter Disabled	1	3	3	4	0	2	-20	-20	0	0	0	10	-0.002	-0.006	0.000	0.000	0.000	0.002
Fuel Pressure High	15	15	14	3	0	0	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.000
Clogged Air Filter	21	19	15	15	15	15	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	5	5	5	5	5	5	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	0	4	5	5	5	5	-20	-20	-20	-20	-20	-10	0.000	-0.008	-0.010	-0.010	-0.010	-0.005
Other Air Problems	9	12	8	8	8	8	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	3	3	2	2	2	2	200	200	300	500	500	250	0.060	0.060	0.060	0.100	0.100	0.050
Excess Oil Consumption	5	5	5	5	3	3	300	300	300	300	300	150	0.150	0.150	0.150	0.150	0.090	0.045
Electronics Failure	0	0	3	3	3	30	0	30	50	50	50	25	0.000	0.000	0.015	0.015	0.015	0.075
Electronics Tampered	0	0	5	5	5	5	0	0	0	0	0	25	0.000	0.000	0.000	0.000	0.000	0.013
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	100	0	0	50	0.000	0.000	0.063	0.000	0.000	0.025
NOx Aftertreatment Malfunction	0	0	0	0	2	17.1	0	0	40	100	100	15	0.000	0.000	0.000	0.000	0.020	0.026
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
													53.9%	265.4%	243.2%	525.8%	523.3%	182.3%

Particulate Matter

Heavy-Heavy-Duty Trucks							Particulate Matter											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	8	13	11	5	2	2	-25	-20	0	0	0	0	-0.0200	-0.0260	0.0000	0.0000	0.0000	0.0000
Timing Retarded	15	12	9	3	2	2	50	25	100	100	100	5	0.0750	0.0300	0.0900	0.0300	0.0200	0.0010
Minor Injection Problems	20	20	15	15	15	13	35	75	75	347	347	17.4	0.0700	0.1500	0.1125	0.5205	0.5205	0.0226
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	200	75	75	347	347	0	0.2000	0.0750	0.0750	0.3470	0.3470	0.0000
NOx Aftertreatment Sensor #2	3	3	3	3	3	2.19	650	75	75	347	347	0	0.1950	0.0225	0.0225	0.1041	0.1041	0.0000
PM Filter leak	29	23	16	4	0	13.9	20	20	50	50	50	600	0.0580	0.0460	0.0800	0.0200	0.0000	0.8358
PM Filter Disabled	30	23	16	4	0	2	50	50	100	100	100	1000	0.1500	0.1150	0.1600	0.0400	0.0000	0.2000
Fuel Pressure High	24	18	13	3	0	0	20	30	30	30	30	1.5	0.0480	0.0540	0.0390	0.0090	0.0000	0.0000
Clogged Air Filter	22	20	15	15	15	15	40	40	50	50	50	2.5	0.0880	0.0800	0.0750	0.0750	0.0750	0.0038
Wrong/Worn Turbo	12	10	5	5	5	5	40	40	50	50	50	2.5	0.0480	0.0400	0.0250	0.0250	0.0250	0.0013
Intercooler Clogged	3	7	5	5	5	5	40	40	50	50	50	2.5	0.0120	0.0280	0.0250	0.0250	0.0250	0.0013
Other Air Problems	15	15	8	8	8	8	40	40	40	40	40	2	0.0600	0.0600	0.0320	0.0320	0.0320	0.0016
Engine Failure	2	2	2	2	2	2	150	150	300	500	500	25	0.0300	0.0300	0.0600	0.1000	0.1000	0.0050
Excess Oil Consumption	2	2	5	5	3	3	120	150	300	600	600	30	0.0240	0.0300	0.1500	0.3000	0.1800	0.0090
Electronics Failure	0	2	3	3	3	30	0	30	60	60	60	3	0.0000	0.0060	0.0180	0.0180	0.0180	0.0090
Electronics Tampered	0	0	5	5	5	5	0	0	50	50	50	2.5	0.0000	0.0000	0.0250	0.0250	0.0250	0.0013
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	40	40	40	2	0.0000	0.0000	0.0253	0.0253	0.0040	0.0010
NOx Aftertreatment Malfunction	0	0	0	0	0	17.1	0	0	200	300	300	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0257
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	-1.5	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0030
													132.4%	93.6%	130.4%	206.5%	170.7%	118.6%

Medium-Heavy-Duty Trucks							Particulate Matter											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	10	10	10	5	2	2	-25	-20	0	0	0	0	-0.0250	-0.0200	0.0000	0.0000	0.0000	0.0000
Timing Retarded	6	6	6	3	2	2	50	25	100	100	100	5	0.0300	0.0150	0.0600	0.0300	0.0200	0.0010
Minor Injection Problems	20	20	15	15	15	13	35	75	75	347	347	17.4	0.0700	0.1500	0.1125	0.5205	0.5205	0.0226
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	200	75	75	347	347	0	0.2000	0.0750	0.0750	0.3470	0.3470	0.0000
NOx Aftertreatment Sensor #2	3	3	3	3	3	2.19	650	75	75	347	347	0	0.1950	0.0225	0.0225	0.1041	0.1041	0.0000
PM Filter leak	18	18	17	4	0	13.9	20	20	50	50	50	600	0.0360	0.0360	0.0850	0.0200	0.0000	0.8358
PM Filter Disabled	15	15	14	4	0	2	50	50	100	100	100	1000	0.0750	0.0750	0.1400	0.0400	0.0000	0.2000
Fuel Pressure High	14	14	14	3	0	0	20	30	30	30	30	1.5	0.0280	0.0420	0.0420	0.0090	0.0000	0.0000
Clogged Air Filter	23	19	15	15	15	15	40	40	50	50	50	2.5	0.0920	0.0760	0.0750	0.0750	0.0750	0.0038
Wrong/Worn Turbo	10	9	5	5	5	5	40	40	50	50	50	2.5	0.0400	0.0360	0.0250	0.0250	0.0250	0.0013
Intercooler Clogged	1	4	5	5	5	5	40	40	50	50	50	2.5	0.0040	0.0160	0.0250	0.0250	0.0250	0.0013
Other Air Problems	14	12	8	8	8	8	40	40	40	40	40	2	0.0560	0.0480	0.0320	0.0320	0.0320	0.0016
Engine Failure	2	2	2	2	2	2	150	150	300	500	500	25	0.0300	0.0300	0.0600	0.1000	0.1000	0.0050
Excess Oil Consumption	3	3	5	5	3	3	120	150	300	600	600	30	0.0360	0.0450	0.1500	0.3000	0.1800	0.0090
Electronics Failure	0	0	3	3	3	30	0	30	60	60	60	3	0.0000	0.0000	0.0180	0.0180	0.0180	0.0090
Electronics Tampered	0	0	5	5	5	5	0	0	50	50	50	2.5	0.0000	0.0000	0.0250	0.0250	0.0250	0.0013
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	40	0	40	2	0.0000	0.0000	0.0240	0.0000	0.0040	0.0010
NOx Aftertreatment Malfunction	0	0	0	0	2	17.1	0	0	200	300	300	15	0.0000	0.0000	0.0000	0.0000	0.0600	0.0257
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	-1.5	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0030
													101.6%	77.2%	122.8%	200.2%	184.6%	118.6%

Light-Heavy-Duty Trucks — Particulate Matter

	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+	Pre 88	88-90	91-93	94-97	98-02	2010+
Timing Advanced	10	10	10	5	2	2	-25	-20	0	0	0	0	-0.0250	-0.0200	0.0000	0.0000	0.0000	0.0000
Timing Retarded	10	10	6	3	2	2	50	25	100	100	100	5	0.0500	0.0250	0.0600	0.0300	0.0200	0.0010
Minor Injection Problems	20	20	15	15	15	13	35	75	75	347	347	17.4	0.0700	0.1500	0.1125	0.5205	0.5205	0.0226
NOx Aftertreatment Sensor #1	10	10	10	10	10	68.1	200	75	75	347	347	0	0.2000	0.0750	0.0750	0.3470	0.3470	0.0000
NOx Aftertreatment Sensor #2	5	5	3	3	3	2.19	650	75	75	347	347	0	0.3250	0.0375	0.0225	0.1041	0.1041	0.0000
PM Filter leak	2	5	5	4	0	13.9	20	20	50	50	50	600	0.0040	0.0100	0.0250	0.0200	0.0000	0.8358
PM Filter Disabled	1	3	3	4	0	2	50	50	100	100	100	1000	0.0050	0.0150	0.0300	0.0400	0.0000	0.2000
Fuel Pressure High	15	15	14	3	0	0	20	30	30	30	30	1.5	0.0300	0.0450	0.0420	0.0090	0.0000	0.0000
Clogged Air Filter	21	19	15	15	15	15	40	40	50	50	50	2.5	0.0840	0.0760	0.0750	0.0750	0.0750	0.0038
Wrong/Worn Turbo	5	5	5	5	5	5	40	40	50	50	50	2.5	0.0200	0.0200	0.0250	0.0250	0.0250	0.0013
Intercooler Clogged	0	4	5	5	5	5	40	40	50	50	50	2.5	0.0000	0.0160	0.0250	0.0250	0.0250	0.0013
Other Air Problems	9	12	8	8	8	8	40	40	40	40	40	2	0.0360	0.0480	0.0320	0.0320	0.0320	0.0016
Engine Failure	3	3	2	2	2	2	150	150	300	500	500	25	0.0450	0.0450	0.0600	0.1000	0.1000	0.0050
Excess Oil Consumption	5	5	5	5	3	3	120	150	300	600	600	30	0.0600	0.0750	0.1500	0.3000	0.1800	0.0090
Electronics Failure	0	0	3	3	3	30	0	30	60	60	60	3	0.0000	0.0000	0.0180	0.0180	0.0180	0.0090
Electronics Tampered	0	0	5	5	5	5	0	0	50	50	50	2.5	0.0000	0.0000	0.0250	0.0250	0.0250	0.0013
Oxy Cat Malfunction	0	0	6	6	1	5	0	0	40	0	40	2	0.0000	0.0000	0.0253	0.0000	0.0040	0.0010
NOx Aftertreatment Malfunction	0	0	0	0	2	17.1	0	0	200	300	300	15	0.0000	0.0000	0.0000	0.0000	0.0600	0.0257
EGR Disabled/Low Flow	0	0	0	0	0	20	0	0	0	0	0	-1.5	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0030
													98.0%	69.9%	95.3%	200.2%	184.6%	118.6%

Heavy-Duty OBD 2010+

Oxides of Nitrogen

Tampered and Mal-maintained Heavy-Heavy-Duty Trucks

	Probability of Occurrence						Oxides of Nitrogen: % Change in Emissions						Oxides of Nitrogen: % change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	8	13	11	5	2	1.33	70	50	60	60	60	21	0.056	0.065	0.066	0.030	0.012	0.003
Timing Retarded	15	12	9	3	2	1.33	-20	-20	-20	-20	-20	-7	-0.030	-0.024	-0.018	-0.006	-0.004	-0.001
Minor Injection Problems	20	20	15	15	15	8.67	-0.5	-5.0	-5.0	-1	-1	-1	-0.001	-0.010	-0.008	-0.002	-0.002	-0.001
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	-5	-5	-5	-1	-1	200	-0.005	-0.005	-0.005	-0.001	-0.001	0.954
NOx Aftertreatment Sensor #2	3	3	3	3	3	3.91	-7	-5	-5	-1	-1	200	-0.002	-0.002	-0.002	0.000	0.000	0.078
PM Filter leak	29	23	16	4	0	9.75	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
PM Filter Disabled	30	23	16	4	0	1.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Pressure High	24	18	13	3	0	0	10	10	10	10	10	2.5	0.024	0.018	0.013	0.003	0.000	0.000
Clogged Air Filter	22	20	15	15	15	10	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	12	10	5	5	5	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	3	7	5	5	5	3.33	20	20	25	25	25	17.5	0.006	0.014	0.013	0.013	0.013	0.006
Other Air Problems	15	15	8	8	8	5.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	1.33	-10	-10	-10	-10	-10	-3.5	-0.002	-0.002	-0.002	-0.002	-0.002	0.000
Excess Oil Consumption	2	2	5	5	3	2	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Failure	0	2	3	3	3	20	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Tampered	0	0	5	5	5	3.33	0	50	80	80	80	28	0.000	0.000	0.040	0.040	0.040	0.009
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
NOx Aftertreatment Malfunction	0	0	0	0	0	12	0	0	0	0	0	300	0.000	0.000	0.000	0.000	0.000	0.360
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	150	0.000	0.000	0.000	0.000	0.000	0.200
													4.6%	5.5%	9.8%	7.6%	5.6%	248.7%

Medium-Heavy-Duty Trucks							Oxides of Nitrogen											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	10	10	10	5	2	1.33	70	50	60	60	60	21	0.070	0.050	0.060	0.030	0.012	0.003
Timing Retarded	6	6	6	3	2	1.33	-20	-20	-20	-20	-20	-7	-0.012	-0.012	-0.012	-0.006	-0.004	-0.001
Minor Injection Problems	20	20	15	15	15	8.67	-0.5	-5.0	-5.0	-1	-1	-1	-0.001	-0.010	-0.008	-0.002	-0.002	-0.001
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	-5	-5	-5	-1	-1	200	-0.005	-0.005	-0.005	-0.001	-0.001	0.954
NOx Aftertreatment Sensor #2	3	3	3	3	3	3.91	-7	-5	-5	-1	-1	200	-0.002	-0.002	-0.002	0.000	0.000	0.078
PM Filter leak	18	18	17	4	0	9.75	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
PM Filter Disabled	15	15	14	4	0	1.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Pressure High	14	14	14	3	0	0	10	10	10	10	10	2.5	0.014	0.014	0.014	0.003	0.000	0.000
Clogged Air Filter	23	19	15	15	15	10	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	10	9	5	5	5	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	1	4	5	5	5	3.33	20	20	25	25	25	17.5	0.002	0.008	0.013	0.013	0.013	0.006
Other Air Problems	14	12	8	8	8	5.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	1.33	-10	-10	-10	-10	-10	-3.5	-0.002	-0.002	-0.002	-0.002	-0.002	0.000
Excess Oil Consumption	3	3	5	5	3	2	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Failure	0	0	3	3	3	20	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Tampered	0	0	5	5	5	3.33	0	50	80	80	80	28	0.000	0.000	0.040	0.040	0.040	0.009
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
NOx Aftertreatment Malfunction	0	0	0	0	2	12	0	0	0	0	0	300	0.000	0.000	0.000	0.000	0.000	0.360
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	150	0.000	0.000	0.000	0.000	0.000	0.200
													6.4%	4.2%	10.0%	7.6%	5.6%	248.7%

Light-Heavy-Duty Trucks							Oxides of Nitrogen											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	10	10	10	5	2	1.33	70	50	60	60	60	21	0.070	0.050	0.060	0.030	0.012	0.003
Timing Retarded	10	10	6	3	2	1.33	-20	-20	-20	-20	-20	-7	-0.020	-0.020	-0.012	-0.006	-0.004	-0.001
Minor Injection Problems	20	20	15	15	15	8.67	-0.5	-5.0	-5.0	-1	-1	-1	-0.001	-0.010	-0.008	-0.002	-0.002	-0.001
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	-5	-5	-5	-1	-1	200	-0.005	-0.005	-0.005	-0.001	-0.001	0.954
NOx Aftertreatment Sensor #2	5	5	3	3	3	3.91	-7	-5	-5	-1	-1	200	-0.004	-0.003	-0.002	0.000	0.000	0.078
PM Filter leak	2	5	5	4	0	9.75	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
PM Filter Disabled	1	3	3	4	0	1.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Fuel Pressure High	15	15	14	3	0	0	10	10	10	10	10	2.5	0.015	0.015	0.014	0.003	0.000	0.000
Clogged Air Filter	21	19	15	15	15	10	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	5	5	5	5	5	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	0	4	5	5	5	3.33	20	20	25	25	25	17.5	0.000	0.008	0.013	0.013	0.013	0.006
Other Air Problems	9	12	8	8	8	5.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	3	3	2	2	2	1.33	-10	-10	-10	-10	-10	-3.5	-0.003	-0.003	-0.002	-0.002	-0.002	0.000
Excess Oil Consumption	5	5	5	5	3	2	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Failure	0	0	3	3	3	20	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Electronics Tampered	0	0	5	5	5	3.33	0	50	80	80	80	28	0.000	0.000	0.040	0.040	0.040	0.009
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
NOx Aftertreatment Malfunction	0	0	0	0	2	12	0	0	0	0	0	300	0.000	0.000	0.000	0.000	0.000	0.360
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	150	0.000	0.000	0.000	0.000	0.000	0.200
													5.3%	3.3%	10.0%	7.6%	5.6%	248.7%

Hydrocarbons

Heavy-Heavy-Duty Trucks							Hydrocarbons											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	8	13	11	5	2	1.33	0	0	30	30	30	15	0.000	0.000	0.033	0.015	0.006	0.002
Timing Retarded	15	12	9	3	2	1.33	50	50	50	50	50	25	0.075	0.060	0.045	0.015	0.010	0.003
Minor Injection Problems	20	20	15	15	15	8.67	7	668	668	1723	1723	862	0.013	1.336	1.002	2.585	2.585	0.747
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	100	668	668	1723	1723	15	0.100	0.668	0.668	1.723	1.723	0.072
NOx Aftertreatment Sensor #2	3	3	3	3	3	3.91	325	668	668	1723	1723	15	0.098	0.200	0.200	0.517	0.517	0.006
PM Filter leak	29	23	16	4	0	9.75	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.010
PM Filter Disabled	30	23	16	4	0	1.33	-20	-20	0	0	0	10	-0.060	-0.046	0.000	0.000	0.000	0.001
Fuel Pressure High	24	18	13	3	0	0	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.000
Clogged Air Filter	22	20	15	15	15	10	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	12	10	5	5	5	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	3	7	5	5	5	3.33	-20	-20	-20	-20	-20	-10	-0.006	-0.014	-0.010	-0.010	-0.010	-0.003
Other Air Problems	15	15	8	8	8	5.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	1.33	200	200	300	500	500	250	0.040	0.040	0.060	0.100	0.100	0.033
Excess Oil Consumption	2	2	5	5	3	2	300	300	300	300	300	150	0.060	0.060	0.150	0.150	0.090	0.030
Electronics Failure	0	2	3	3	3	20	0	30	50	50	50	25	0.000	0.006	0.015	0.015	0.015	0.050
Electronics Tampered	0	0	5	5	5	3.33	0	0	0	0	0	25	0.000	0.000	0.000	0.000	0.000	0.008
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	100	0	0	50	0.000	0.000	0.063	0.000	0.000	0.017
NOx Aftertreatment Malfunction	0	0	0	0	0	12	0	0	40	100	100	15	0.000	0.000	0.000	0.000	0.000	0.018
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
													31.5%	231.3%	248.2%	525.8%	512.4%	115.1%

Medium-Heavy-Duty Trucks							Hydrocarbons											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	10	10	10	5	2	1.33	0	0	30	30	30	15	0.000	0.000	0.030	0.015	0.006	0.002
Timing Retarded	6	6	6	3	2	1.33	50	50	50	50	50	25	0.030	0.030	0.030	0.015	0.010	0.003
Minor Injection Problems	20	20	15	15	15	8.67	7	668	668	1723	1723	862	0.013	1.336	1.002	2.585	2.585	0.747
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	100	668	668	1723	1723	15	0.100	0.668	0.668	1.723	1.723	0.072
NOx Aftertreatment Sensor #2	3	3	3	3	3	3.91	325	668	668	1723	1723	15	0.098	0.200	0.200	0.517	0.517	0.006
PM Filter leak	18	18	17	4	0	9.75	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.010
PM Filter Disabled	15	15	14	4	0	1.33	-20	-20	0	0	0	10	-0.030	-0.030	0.000	0.000	0.000	0.001
Fuel Pressure High	14	14	14	3	0	0	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.000
Clogged Air Filter	23	19	15	15	15	10	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	10	9	5	5	5	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	1	4	5	5	5	3.33	-20	-20	-20	-20	-20	-10	-0.002	-0.008	-0.010	-0.010	-0.010	-0.003
Other Air Problems	14	12	8	8	8	5.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	2	2	2	2	2	1.33	200	200	300	500	500	250	0.040	0.040	0.060	0.100	0.100	0.033
Excess Oil Consumption	3	3	5	5	3	2	300	300	300	300	300	150	0.090	0.090	0.150	0.150	0.090	0.030
Electronics Failure	0	0	3	3	3	20	0	30	50	50	50	25	0.000	0.000	0.015	0.015	0.015	0.050
Electronics Tampered	0	0	5	5	5	3.33	0	0	0	0	0	25	0.000	0.000	0.000	0.000	0.000	0.008
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	100	0	0	50	0.000	0.000	0.060	0.000	0.000	0.017
NOx Aftertreatment Malfunction	0	0	0	0	2	12	0	0	40	100	100	15	0.000	0.000	0.000	0.000	0.020	0.018
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
													33.7%	230.8%	242.2%	525.8%	523.3%	115.1%

Light-Heavy-Duty Trucks							Hydrocarbons											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	10	10	10	5	2	1.33	0	0	30	30	30	15	0.000	0.000	0.030	0.015	0.006	0.002
Timing Retarded	10	10	6	3	2	1.33	50	50	50	50	50	25	0.050	0.050	0.030	0.015	0.010	0.003
Minor Injection Problems	20	20	15	15	15	8.67	7	668	668	1723	1723	862	0.013	1.336	1.002	2.585	2.585	0.747
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	100	668	668	1723	1723	15	0.100	0.668	0.668	1.723	1.723	0.072
NOx Aftertreatment Sensor #2	5	5	3	3	3	3.91	325	668	668	1723	1723	15	0.163	0.334	0.200	0.517	0.517	0.006
PM Filter leak	2	5	5	4	0	9.75	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.010
PM Filter Disabled	1	3	3	4	0	1.33	-20	-20	0	0	0	10	-0.002	-0.006	0.000	0.000	0.000	0.001
Fuel Pressure High	15	15	14	3	0	0	0	0	0	0	0	10	0.000	0.000	0.000	0.000	0.000	0.000
Clogged Air Filter	21	19	15	15	15	10	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Wrong/Worn Turbo	5	5	5	5	5	3.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Intercooler Clogged	0	4	5	5	5	3.33	-20	-20	-20	-20	-20	-10	0.000	-0.008	-0.010	-0.010	-0.010	-0.003
Other Air Problems	9	12	8	8	8	5.33	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
Engine Failure	3	3	2	2	2	1.33	200	200	300	500	500	250	0.060	0.060	0.060	0.100	0.100	0.033
Excess Oil Consumption	5	5	5	5	3	2	300	300	300	300	300	150	0.150	0.150	0.150	0.150	0.090	0.030
Electronics Failure	0	0	3	3	3	20	0	30	50	50	50	25	0.000	0.000	0.015	0.015	0.015	0.050
Electronics Tampered	0	0	5	5	5	3.33	0	0	0	0	0	25	0.000	0.000	0.000	0.000	0.000	0.008
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	100	0	0	50	0.000	0.000	0.063	0.000	0.000	0.017
NOx Aftertreatment Malfunction	0	0	0	0	2	12	0	0	40	100	100	15	0.000	0.000	0.000	0.000	0.020	0.018
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
													53.9%	265.4%	243.2%	525.8%	523.3%	115.1%

Particulate Matter

Heavy-Heavy-Duty Trucks							Particulate Matter											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	8	13	11	5	2	1.33	-25	-20	0	0	0	0	-0.0200	-0.0260	0.0000	0.0000	0.0000	0.0000
Timing Retarded	15	12	9	3	2	1.33	50	25	100	100	100	5	0.0750	0.0300	0.0900	0.0300	0.0200	0.0007
Minor Injection Problems	20	20	15	15	15	8.67	35	75	75	347	347	17.4	0.0700	0.1500	0.1125	0.5205	0.5205	0.0150
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	200	75	75	347	347	0	0.2000	0.0750	0.0750	0.3470	0.3470	0.0000
NOx Aftertreatment Sensor #2	3	3	3	3	3	3.91	650	75	75	347	347	0	0.1950	0.0225	0.0225	0.1041	0.1041	0.0000
PM Filter leak	29	23	16	4	0	9.75	20	20	50	50	50	600	0.0580	0.0460	0.0800	0.0200	0.0000	0.5850
PM Filter Disabled	30	23	16	4	0	1.33	50	50	100	100	100	1000	0.1500	0.1150	0.1600	0.0400	0.0000	0.1333
Fuel Pressure High	24	18	13	3	0	0	20	30	30	30	30	1.5	0.0480	0.0540	0.0390	0.0090	0.0000	0.0000
Clogged Air Filter	22	20	15	15	15	10	40	40	50	50	50	2.5	0.0880	0.0800	0.0750	0.0750	0.0750	0.0025
Wrong/Worn Turbo	12	10	5	5	5	3.33	40	40	50	50	50	2.5	0.0480	0.0400	0.0250	0.0250	0.0250	0.0008
Intercooler Clogged	3	7	5	5	5	3.33	40	40	50	50	50	2.5	0.0120	0.0280	0.0250	0.0250	0.0250	0.0008
Other Air Problems	15	15	8	8	8	5.33	40	40	40	40	40	2	0.0600	0.0600	0.0320	0.0320	0.0320	0.0011
Engine Failure	2	2	2	2	2	1.33	150	150	300	500	500	25	0.0300	0.0300	0.0600	0.1000	0.1000	0.0033
Excess Oil Consumption	2	2	5	5	3	2	120	150	300	600	600	30	0.0240	0.0300	0.1500	0.3000	0.1800	0.0060
Electronics Failure	0	2	3	3	3	20	0	30	60	60	60	3	0.0000	0.0060	0.0180	0.0180	0.0180	0.0060
Electronics Tampered	0	0	5	5	5	3.33	0	0	50	50	50	2.5	0.0000	0.0000	0.0250	0.0250	0.0250	0.0008
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	40	40	40	2	0.0000	0.0000	0.0253	0.0253	0.0040	0.0007
NOx Aftertreatment Malfunction	0	0	0	0	0	12	0	0	200	300	300	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0180
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	-1.5	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0020
													132.4%	93.6%	130.4%	206.5%	170.7%	80.5%

Medium-Heavy-Duty Trucks							Particulate Matter											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	10	10	10	5	2	1.33	-25	-20	0	0	0	0	-0.0250	-0.0200	0.0000	0.0000	0.0000	0.0000
Timing Retarded	6	6	6	3	2	1.33	50	25	100	100	100	5	0.0300	0.0150	0.0600	0.0300	0.0200	0.0007
Minor Injection Problems	20	20	15	15	15	8.67	35	75	75	347	347	17.4	0.0700	0.1500	0.1125	0.5205	0.5205	0.0150
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	200	75	75	347	347	0	0.2000	0.0750	0.0750	0.3470	0.3470	0.0000
NOx Aftertreatment Sensor #2	3	3	3	3	3	3.91	650	75	75	347	347	0	0.1950	0.0225	0.0225	0.1041	0.1041	0.0000
PM Filter leak	18	18	17	4	0	9.75	20	20	50	50	50	600	0.0360	0.0360	0.0850	0.0200	0.0000	0.5850
PM Filter Disabled	15	15	14	4	0	1.33	50	50	100	100	100	1000	0.0750	0.0750	0.1400	0.0400	0.0000	0.1333
Fuel Pressure High	14	14	14	3	0	0	20	30	30	30	30	1.5	0.0280	0.0420	0.0420	0.0090	0.0000	0.0000
Clogged Air Filter	23	19	15	15	15	10	40	40	50	50	50	2.5	0.0920	0.0760	0.0750	0.0750	0.0750	0.0025
Wrong/Worn Turbo	10	9	5	5	5	3.33	40	40	50	50	50	2.5	0.0400	0.0360	0.0250	0.0250	0.0250	0.0008
Intercooler Clogged	1	4	5	5	5	3.33	40	40	50	50	50	2.5	0.0040	0.0160	0.0250	0.0250	0.0250	0.0008
Other Air Problems	14	12	8	8	8	5.33	40	40	40	40	40	2	0.0560	0.0480	0.0320	0.0320	0.0320	0.0011
Engine Failure	2	2	2	2	2	1.33	150	150	300	500	500	25	0.0300	0.0300	0.0600	0.1000	0.1000	0.0033
Excess Oil Consumption	3	3	5	5	3	2	120	150	300	600	600	30	0.0360	0.0450	0.1500	0.3000	0.1800	0.0060
Electronics Failure	0	0	3	3	3	20	0	30	60	60	60	3	0.0000	0.0000	0.0180	0.0180	0.0180	0.0060
Electronics Tampered	0	0	5	5	5	3.33	0	0	50	50	50	2.5	0.0000	0.0000	0.0250	0.0250	0.0250	0.0008
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	40	0	40	2	0.0000	0.0000	0.0240	0.0000	0.0040	0.0007
NOx Aftertreatment Malfunction	0	0	0	0	2	12	0	0	200	300	300	15	0.0000	0.0000	0.0000	0.0000	0.0600	0.0180
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	-1.5	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0020
													101.6%	77.2%	122.8%	200.2%	184.6%	80.5%

Light-Heavy-Duty Trucks							Particulate Matter											
	Probability of Occurrence						% Change in Emissions						% change in Fleet EF					
	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+	Pre 88	88-90	91-93	94-97	98-02	2002+
Timing Advanced	10	10	10	5	2	1.33	-25	-20	0	0	0	0	-0.0250	-0.0200	0.0000	0.0000	0.0000	0.0000
Timing Retarded	10	10	6	3	2	1.33	50	25	100	100	100	5	0.0500	0.0250	0.0600	0.0300	0.0200	0.0007
Minor Injection Problems	20	20	15	15	15	8.67	35	75	75	347	347	17.4	0.0700	0.1500	0.1125	0.5205	0.5205	0.0150
NOx Aftertreatment Sensor #1	10	10	10	10	10	47.7	200	75	75	347	347	0	0.2000	0.0750	0.0750	0.3470	0.3470	0.0000
NOx Aftertreatment Sensor #2	5	5	3	3	3	3.91	650	75	75	347	347	0	0.3250	0.0375	0.0225	0.1041	0.1041	0.0000
PM Filter leak	2	5	5	4	0	9.75	20	20	50	50	50	600	0.0040	0.0100	0.0250	0.0200	0.0000	0.5850
PM Filter Disabled	1	3	3	4	0	1.33	50	50	100	100	100	1000	0.0050	0.0150	0.0300	0.0400	0.0000	0.1333
Fuel Pressure High	15	15	14	3	0	0	20	30	30	30	30	1.5	0.0300	0.0450	0.0420	0.0090	0.0000	0.0000
Clogged Air Filter	21	19	15	15	15	10	40	40	50	50	50	2.5	0.0840	0.0760	0.0750	0.0750	0.0750	0.0025
Wrong/Worn Turbo	5	5	5	5	5	3.33	40	40	50	50	50	2.5	0.0200	0.0200	0.0250	0.0250	0.0250	0.0008
Intercooler Clogged	0	4	5	5	5	3.33	40	40	50	50	50	2.5	0.0000	0.0160	0.0250	0.0250	0.0250	0.0008
Other Air Problems	9	12	8	8	8	5.33	40	40	40	40	40	2	0.0360	0.0480	0.0320	0.0320	0.0320	0.0011
Engine Failure	3	3	2	2	2	1.33	150	150	300	500	500	25	0.0450	0.0450	0.0600	0.1000	0.1000	0.0033
Excess Oil Consumption	5	5	5	5	3	2	120	150	300	600	600	30	0.0600	0.0750	0.1500	0.3000	0.1800	0.0060
Electronics Failure	0	0	3	3	3	20	0	30	60	60	60	3	0.0000	0.0000	0.0180	0.0180	0.0180	0.0060
Electronics Tampered	0	0	5	5	5	3.33	0	0	50	50	50	2.5	0.0000	0.0000	0.0250	0.0250	0.0250	0.0008
Oxy Cat Malfunction	0	0	6	6	1	3.33	0	0	40	0	40	2	0.0000	0.0000	0.0253	0.0000	0.0040	0.0007
NOx Aftertreatment Malfunction	0	0	0	0	2	12	0	0	200	300	300	15	0.0000	0.0000	0.0000	0.0000	0.0600	0.0180
EGR Disabled/Low Flow	0	0	0	0	0	13.3	0	0	0	0	0	-1.5	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0020
													98.0%	69.9%	95.3%	200.2%	184.6%	80.5%