WHITE PAPER

MARCH 2016

REVIEW OF LDV OBD REQUIREMENTS UNDER THE EUROPEAN, KOREAN AND CALIFORNIAN EMISSION PROGRAMS

Francisco Posada and John German

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

ACKNOWLEDGEMENTS

The authors thank the on-board diagnostics branch staff at the California Air Resources Board for their detailed review and constructive comments. Additionally, the authors would like to thank their colleagues, Hui He and Sarah Keller, for shaping the final report. This work was supported by the Energy Foundation China.

For additional information:
International Council on Clean Transportation
1225 I Street NW Suite 900
Washington, DC 20005 USA

communications@theicct.org | www.theicct.org | @TheICCT

TABLE OF CONTENTS

Executive Summary .... **ii**

1. Introduction **1**

Background 1

Scope 1

2. OBD requirements under the European, South Korean and Californian programs **2**

2.1 General OBD system requirements 2

2.2 In-use monitor performance ratio definition 5

2.3 Monitoring requirements 7

2.4 OBD threshold limits 10

2.5 Durability requirements 12

2.6 Communication protocols 12

3. Provisions on anti-tampering and fraudulent passing I/M testing **13**

3.1 Permanent DTC 13

3.2 I/M readiness bits 14

3.3 Calibration identification and calibration verification number 14

4. Certification and conformity of production process for manufacturers **16**

4.1 Type-approval/certification of OBD systems 16

4.2 Production vehicle evaluation testing 22

4.3 OBD deficiencies 24

5. Enforcement **26**

5.1 California 26

5.2 Korea 26

5.3 Europe 26

6. Summary overview of OBD programs **27**

7. Conclusions and recommendations for China **29**

8. References **31**

EXECUTIVE SUMMARY

On-board diagnostic (OBD) systems monitor the performance of engine and aftertreatment components, especially those responsible for controlling harmful pollutant emissions. The OBD system does not directly measure emissions but detects system malfunctions that could potentially lead to high emissions. In a practical sense, OBD systems are designed to help ensure proper operation of the vehicle emission control equipment, alerting the driver in case of malfunctions, so that vehicles are properly maintained and meet emissions limits during the lifetime of use.

Given that China is exploring the adoption of OBD requirements for light-duty vehicles (LDV) compatible with future China 6 vehicle emissions regulations for light-duty vehicles, this report takes a close look at three potential alternatives for OBD regulatory requirements that can be incorporated into the China 6 proposal: Korean OBD II, European OBD Euro 6, and Californian OBD II regulations.

This analysis compares these three OBD programs with respect to technical and regulatory elements. The analysis presents the three programs side by side, exploring similarities and differences on the following main OBD program technical elements: emission control systems monitored, monitoring conditions, OBD emission thresholds, frequency of monitoring, and communication protocols, among others. Also the OBD elements that are relevant to inspection and maintenance (I/M) programs are compared; these elements are designed to prevent fraudulent passing inspections and tampering, improving the effectiveness of I/M programs.

The main findings are:

- California's OBD II program is the most comprehensive program in the world and the basis of the European and Korean programs. This program sets the bar for general OBD requirements, malfunction indication light (MIL) illumination and diagnostic trouble code (DTC) storage, readiness bits and so on, as well as for monitoring conditions. This program has specific OBD threshold limits (OTL) by emission control system and established clear criteria for malfunctions, monitoring conditions, MIL activation and DTC storage and erasing. The California program has the most comprehensive set of demonstration testing, before commercializing the vehicles, and product verification testing following vehicle commercialization.
- The Korean program (KOBD) is second in complexity and level of detail. It covers most of the monitoring requirements of the California Air Resources Board (CARB) program, leaving out only the product verification sections. One downside of the current KOBD program is that it adopted the European OBD (EOBD) requirements for diesel passenger vehicles, as opposed to the CARB OBD requirements for diesels. This follows the fact that the diesel vehicles in Korea are certified to European standards.
- The first shortcoming of the Korean OBD program is that diesel vehicles have much simpler requirements than gasoline vehicles. The emission thresholds are much more lenient, close to Euro 6-1 values.
- The second important shortcoming of the Korean OBD program is related to communication protocols. In order to have a successful I/M program there needs to be reliable, standardized communication between the vehicle and the test device, and the only way to ensure that occurs is through production vehicle evaluation (PVE) communication testing.

- The European program is the most simple of the three programs. It leaves many of the emission control system requirements under "other emission control systems," instead of clearly defining them as is the case for OBD II and KOBD. The European Euro 6 OBD program offers an improved version compared to the current China-5 OBD program but leaves many monitoring requirements open for interpretation

Based on the main findings of this work, the ICCT recommends adopting CA OBDII, including the specific requirements for diesel vehicles, as part of the adoption of China 6 emission standards. The Euro 6 OBD program is not as comprehensive as the Korean and the Californian OBD programs, leaving several emission control systems monitoring requirements open to interpretation. The Korean program is very similar to the Californian OBD program, resulting in similar level of effort for implementation, but its shortcomings on evaluation of communication protocols and treatment of diesel vehicles makes it a less desirable option. Moreover, in light of Volkswagen's recently admitting to cheating on the U.S. certification of diesel vehicles, and given the growing need to meet fuel consumption standards, a more robust set of regulatory requirements for diesels is needed in all countries, including China. Adopting CA OBDII requirements for China 6 could be phased-in with the new standards, while giving additional time to the implementation of requirements for diesel vehicles. This phase-in time is needed to develop capacity among manufacturers and authorities for developing, adopting and implementing the CA OBD II requirements.

California adopted in September 2015 a set of amendments to its OBD II requirements. Although some of those new requirements are specific to LEV-III emissions standard limits, other provisions relevant to vehicle activity and fuel consumption tracking, as well as access to vehicle data for on-road emission testing with portable systems, could be adopted by China as quickly as possible. The data gathered on vehicle activity and fuel consumption could be used to verify new vehicle fuel consumption information that is used by manufacturers for fuel consumption targets compliance, to improve off-cycle credit assessments, and to better evaluate national CO_2 inventories and fuel consumption. Access to data for emission testing with portable systems is a key component of robust compliance and enforcement programs on air-pollution emission standards.

OBD FOR INSPECTION AND MAINTENANCE PROGRAMS

The ICCT recommends adopting these advanced OBD programs as part of the Inspection and Maintenance (I/M) programs for LDVs. This should include access to diagnostic trouble codes (DTCs), readiness bits, reading calibration ID (CAL ID) and calibration verification numbers (CVN), and the development of a national database for these codes. The ICCT also recommends managing of in-use monitor performance ratios (IUMPR) data by national authorities, through the I/M program, to keep track of OBD system performance in use, identify potential deficiencies, and address them in a timely manner.

1. INTRODUCTION

On-board diagnostic (OBD) systems monitor the performance of engine and aftertreatment components, including those responsible for controlling emissions. The OBD system does not directly measure emissions but detects system malfunctions that could potentially lead to high emissions.

The OBD system is designed to help ensure proper operation of the emission control equipment, alerting the driver in the case of malfunctions, so that vehicles meet emission limits during everyday use. OBD systems are a valuable tool for vehicle owners and technicians, as they supply important feedback about engine maintenance needs and point toward potentially urgent repairs. OBD assists in the service and repair of vehicles by providing a simple, quick, and cost-effective way to identify problems by retrieving vital automobile diagnostics data. OBD systems are also a vital component of inspection and maintenance programs for reducing in-use emissions by identifying high-emitting vehicles that are in need of repairs. OBD is also the primary means by which components covered by emissions warranty are identified.

BACKGROUND

Diagnostic systems were first deployed in gasoline light-duty vehicles (LDVs). General Motors began introducing diagnostic systems in its vehicles in 1980. California, which is allowed by the federal government to set its own emission rules due to historic air quality challenges, issued the first requirements for OBD systems starting with the 1991 model year, and Europe followed 10 years later. Those first OBD systems were basic and had very little standardization, meaning that each manufacturer adopted a different system to read and communicate data to drivers and mechanics. By the 1996 model year, the effectiveness of the OBD requirements were greatly enhanced in the United States, and OBD system communications were standardized, for all new vehicles sold in the U.S.

Korea OBD (KOBD) has been mandatory for gasoline and diesel LDVs since 2005 and 2006, respectively. Current gasoline OBD requirements are similar to CARB 1968.2.

SCOPE

Given that China is exploring the adoption of OBD requirements for LDVs compatible with future China 6 regulations, this report takes a close look at three potential alternatives: Korean OBD II, European OBD Euro 6, and Californian OBD II regulations. This analysis compares these three OBD programs and discusses the best option for China, considering emissions benefits and the resources required for manufacturers and regulators.

2. OBD REQUIREMENTS UNDER THE EUROPEAN, SOUTH KOREAN AND CALIFORNIAN PROGRAMS

The OBD requirements presented in this section provide an overview of the general requirements regarding malfunction detection, fault codes and monitoring conditions, as well as the specific monitoring requirements for emission control systems (e.g., catalysts, oxygen sensors, evaporative systems).

This chapter also explores all of the regulatory requirements that compose OBD systems under the three main regulatory programs covered here for LDVs: Europe, Korea and California. Each subsection introduces the topic, then explores the adoption level and the differences across programs. The chapter ends with a summary table that compiles all the monitoring requirements by program.

2.1 GENERAL OBD SYSTEM REQUIREMENTS

Independent of program origin, the general OBD requirements describe when and how the OBD system must operate, and the basic rules to convey the information to the driver/mechanic. This includes detecting the malfunction, storing a trouble code, activating the malfunction indication light (MIL) and defining the contents of the freeze frame information. The OBD general requirements also cover the type of connector and communication protocol that is relevant for inspection and maintenance (I/M) programs and mechanics.

The specific aspects of monitoring conditions–when, for how long or after how many engine operation cycles, and a very closely related concept, the in-use monitor performance ratio (IUMPR)—are described in the next section.

Malfunction indication light and diagnostics trouble code requirements

The MIL, also known as the check engine/service engine light, is part of the OBD system that alerts the driver to potential problems that can lead to high emissions. MIL activation signals the driver to take action and find a solution to the root problem that caused the MIL to turn on. The MIL can be turned off and the malfunction code erased by the technician once the problem is fixed. The OBD system can also extinguish the MIL and erase the fault code if further monitoring indicates the fault is no longer active.

MIL activation occurs only after a series of verification steps have been carried out by the OBD system in order to ensure that the MIL corresponds to a real malfunction and not to spurious circumstances. Under the CARB program, upon detecting a malfunction, the OBD system stores the *pending fault* code, indicating a likely area of malfunction; if the malfunction is found again in the following driving cycle during which monitoring occurs, the stored trouble code becomes a *confirmed code* and the MIL is then activated. If the malfunction is not found again, the pending fault code is erased. The U.S. Environmental Protection Agency (EPA) program refers to pending and confirmed codes as *detected* and *verified* malfunction codes. Pending and/or confirmed diagnostic trouble codes (DTCs) can be downloaded from the vehicle with an OBD scan tool.

A DTC is a standardized method by which vehicle manufacturers communicate their malfunction trouble codes to an OBD scan tool for the purpose of addressing the malfunction. Fault codes are defined and standardized under SAE's J2012

Recommended Practice. DTCs are structured as five-character codes, usually starting with a P for powertrain (emission relevant). The next character in the DTC indicates whether the code is an SAE generic code, which applies to all OBD II systems, or is specific to the vehicle manufacturer. The remaining three characters provide information regarding the specific vehicle system and circuit. As an example relevant to emission control, the code P0304 says to the technician that a powertrain issue (P) has been detected, the code is generic (0), the issue is in the area of the ignition system or misfire (3), and the specific issue is a misfire detected in cylinder four (04). DTCs also provide information on important issues beyond emission malfunctions, such as safety components e.g., anti-lock braking systems (ABS) and traction control systems.

Vehicle fuel economy and activity tracking requirements

California recently approved a broad amendment to the OBD II regulation, including the adoption of data stream parameters that can be used to characterize the vehicle's fuel consumption and activity during normal operational use. This particular element of the amendment would cover new vehicles in model year 2019 and beyond.[1] This amendment was the result of efforts to close the gap between the fuel economy data from certification testing and the fuel economy that is experienced by drivers. This fuel economy and CO_2 emissions gap comes from certification testing limitations and new technologies in the market. Flexibilities in the type-approval procedure allow for unrealistically low driving resistances and unrepresentative conditions during laboratory testing that account for the majority of the gap. Fuel-saving technologies such as stop-start systems and hybrid powertrains also prove more effective at reducing fuel consumption and CO_2 emissions during laboratory testing than during real-world driving. Lastly, under the European program the type-approval process fails to take into consideration auxiliary devices such as air conditioning and entertainment systems; these devices consume energy during real-world driving and thus contribute to the gap. Note that the U.S. fuel economy label program does account for air conditioning operation.

The data gathered under this vehicle fuel economy and activity tracking requirement would be used to verify the fuel economy label and CO_2 data that are used for compliance with the fuel economy and CO_2 targets. Also, the data can be used to verify off-cycle credits that are being granted to manufacturers for some technologies that provide fuel benefits outside the testing laboratory conditions. In addition, the data gathered could be used to improve fuel economy and CO_2 targets in the future, as well as better represent the fuel consumed and CO_2 savings for national reductions under international emission agreements.

The OBD data required from new vehicles starting in 2019 model year are:

- Total engine run time
- Total idle run time (with "idle" defined in section (g)(6.1.2))
- Cumulative distance traveled
- Cumulative fuel consumed by the vehicle
- Cumulative positive kinetic energy (with "positive kinetic energy" defined by the equation below when final velocity is greater than initial velocity evaluated on a 1 Hz basis): Positive kinetic energy = $(1/\text{distance}) * \sum[(\text{final velocity})^2 - (\text{initial velocity})^2]$

1 Other amendments have different implementation dates. As an example, positive crankcase ventilation system monitoring will be to phase in between 2023 and 2025 model year.

- Cumulative calculated engine output torque (with “calculated engine output torque” defined as the net brake torque produced by the engine)
- Cumulative propulsion system active time
- Cumulative idle propulsion system active time (with “idle propulsion system active time” defined as the time when the vehicle is in a state of propulsion system active, accelerator pedal released by driver, and vehicle speed is less than or equal to one mile per hour)
- Cumulative city propulsion system active time (with “city propulsion system active time” defined as the time when the vehicle is in a state of propulsion system active and the vehicle speed is greater than one mile per hour and less than or equal to 40 miles per hour)

Dividing the total fuel consumed by the total distance traveled, stakeholders can have a unique access to average fuel consumption for each vehicle on the road fitted with this data stream. The inclusion of positive kinetic energy gives a sense of the severity of driving styles, aggressive or mild. Total idle time helps monitor the fleet’s operation under idle time, an important indicator of the fuel economy potential for off-cycle credits. Gathering this information during annual inspection and maintenance would provide manufactures, regulators, researchers and vehicle owners with an unprecedented set of data for better policy design.

Additional requirements are set for plug-in hybrids, such as cumulative distances traveled under battery charge depletion with engine on and with engine off, and other essential data for understanding the CO_2 emissions from plug-in hybrid electric vehicles as they are being used in the real world and to inform future rulemaking changes regarding proper credit for their greenhouse gas benefits. Vehicles with active technologies are also required to monitor the time the technology is active.

In a separate section, the amendment calls for broadcasting of some parameters related to portable emission measurement systems (PEMS) that are used for compliance and enforcement activities. The parameters are: calculated load, torque, fuel rate, and modeled exhaust gas flow. These signals would be available on demand through the standardized data link connector in accordance with SAE J1979 specifications.

Freeze frame

Freeze frame is a featured shared by EOBD, KOBD and OBD II that captures, and freezes, relevant engine and system information at the time the DTC is stored. Freeze frame data are designed to help understand the conditions faced by the vehicle when the DTC was flagged, facilitating the process to solve the malfunction. Typical freeze frame data stored by the OBD systems include:

- Calculated engine load (in percent)
- Engine RPM
- Short- and long-term fuel trim (in percent)
- Fuel pressure (if available)
- Closed/open loop air fuel management operation
- Manifold absolute pressure

- The DTC that caused the freeze frame to be stored
- If the code is related to misfire, the cylinder that experienced it

Monitoring conditions

The California regulation establishes general requirements for monitoring, then proceeds to present the specifics by system, which are shown in the Monitoring Requirements section below. The main aspect for monitoring is that manufacturers define the monitoring conditions for all the relevant systems and all those are subject to the executive officer approval through the certification process. The approval depends upon demonstrating with technical documentation that the monitoring conditions are robust enough to detect malfunctions and that the monitoring conditions are designed to occur during normal urban driving conditions—a concept closely related to IUMPR, which is shown next—and verifiable during chassis testing.

2.2 IN-USE MONITOR PERFORMANCE RATIO DEFINITION

The U.S. and European programs have adopted IUMPR monitoring values that require a minimum frequency of monitoring events per drive cycle. IUMPR can be defined more specifically as the number of drive cycles[2] in which the OBD monitor makes an evaluation (numerator) to the number of drive cycles that meet legislated minimum general OBD monitoring conditions (denominator). For example, in the United States, the minimum IUMPR is 0.1, meaning that there should be at least one monitoring event during 10 qualified driving cycles. CARB requires an IUMPR of 0.336 for catalytic converters, meaning at least one monitoring event in three qualified driving cycles. On the other side of the spectrum, systems that are continuously monitored (i.e., fuel system, and misfire) have sampling rates above two times per second.

The numerator is defined as the number of times a vehicle has been operated when all monitoring conditions necessary for a specific monitor to detect a malfunction have been encountered. The numerator value increments by an integer of one. The conditions for the numerator to increase are: it can increase only one time per driving cycle; it increases within 10 seconds when all the conditions for that system monitoring have been completed.

For monitors that run or complete during engine off operation, such as certain evaporative monitor strategies, the numerator shall be incremented within 10 seconds after the monitor has completed during engine off operation or during the first 10 seconds of engine start on the subsequent driving cycle.

The denominator is a counter indicating the number of vehicle driving events, taking into account special conditions for a specific monitor. The denominator is incremented once per driving cycle, if during this driving cycle the following conditions are met:

a) Cumulative engine on for more than 10 minutes under specific ambient temperature conditions (T> 20 °F) and below certain altitudes.

b) Cumulative vehicle operation at or above 25 mph occurs for greater than or equal to 5 minutes under the same temperature and altitude conditions.

2 A drive cycle consists of engine startup and engine shutoff and includes the period of engine off time up to the next engine startup. For vehicles that employ engine start-stop technology, a drive cycle can be alternatively defined as key-on to key-off cycle.

c) Continuous vehicle operation at idle for more than 30 seconds under the same temperature and altitude conditions.

For the evaporative system there are special conditions for denominator change:

a) Cumulative time since engine start is greater than or equal to 10 minutes. The temperature conditions are bounded between 40 °F and 95 °F.

b) Engine cold start occurs with engine coolant temperature at engine start bounded between 40 °F and 95 °F and less than or equal to 12 °F higher than ambient temperature at engine start.

Also, the denominator for those components activates only during engine startup or for cold start operation, such as the cold start reduction strategy, and only change by one integer if the component or system is active for more than 10 seconds. This 10 seconds active requirement is in addition to the previously described general denominator.

The denominators of systems that are temporary activated, such as variable valve timing (VVT) systems or turbo chargers waste gates, increment by one integer once the system has been active more than twice for more than 2 seconds or after accumulated 10 seconds in operation. The European program calls for two or more occasions during the driving cycle or for a time greater than or equal to 10 seconds.

For diesel vehicles the CARB regulation has specific requirements for denominator changes for diesel particulate filters (DPF) and diesel oxidation catalysts (DOC). First it has to be operated over a driving cycle that meets the requirements for a general denominator subsequent to the last time the denominator incremented, and a total of 500 miles or 800 km have been driven since that last denominator increase. These specific conditions for denominator change apply to nonmethane hydrocarbon (NMHC) catalysts, and particulate matter (PM) filters, for catalytic conversion efficiency, filtering performance and missing substrate.

The ratios are naturally defined as the result of dividing numerator by denominator. The minimum acceptable IUMPRs for the relevant systems are presented in Table 1. The letter R next to the ratio value means in that the manufacturers are required to implement software algorithms in the OBD II system to individually track and report in-use performance ratios of those systems to a scan tool request. CARB, Korea, and Euro 6-2 all have IUMPR requirements to ensure that monitoring conditions implemented by the manufacturer will provide adequate frequency of monitoring during in-use vehicle operation. Comparison of IUMPR numbers gives an indication of how often a specific monitor is required to be operating relative to vehicle operation under that OBD program.

Table 1. Summary of IUMPR values and reporting requirements for OBD systems under the California, Korean and European regulations.

OBD systems	California (CCRC 2013)	Korea post 2016 (MOE 2015)	Euro 6c 2017 (UNECE, 2015)
Gasoline vehicles			
Catalyst (each bank separately)	0.336 R	0.336R	0.336 R
Misfire monitoring	Continuous	Continuous	—
Evaporative system monitoring	0.26 R purge flow and vapor leaks	0.26-0.62* R purge flow and vapor leaks	0.52 (SI) R purge control valve
Secondary air system	0.26 R	0.26 R	0.336 R
Fuel system	Continuous. Air-Fuel Balance monitoring: 0.1	Continuous	—
Exhaust gas sensor monitoring (monitored separately)	0.336 R	0.336 R	0.336 R
Exhaust gas recirculation (EGR)	0.336 R	0.336 R	0.336 R
Cold start emission reduction strategy	0.26	0.26	0.26 R
Variable valve timing and/or control (VVT)	0.336 R	0.336 R	0.336 R
Diesel vehicles			
DOC	0.336	0.336	0.336 R
DPF	0.336 R	0.336 R	0.336 R
Selective catalytic reduction (SCR) and lean NO_x traps (LNT)	0.336 R	0.336 R	0.26 R
NO_x sensors	0.336	0.336	0.336
EGR	0.336	0.336	0.336
Boost	0.336 R	0.336 R	0.336 R
Fuel injection system	0.336 R	0.336 R	—

*IUMPR of 0.26 for 0.5mm leak and 0.62 for 2.3mm leak

2.3 MONITORING REQUIREMENTS

OBD monitoring requirements are set for each vehicle system, and can be split into two categories: requirements that include emission threshold monitoring and requirements that cover general system functionality.

Threshold monitoring requirements apply to the most critical emission control systems. The MIL is activated when sensors infer/detect a malfunction that has been previously correlated in the laboratory with emission levels above certain limit values. Each limit value is set as a multiplier of the emission standard limit (e.g., 1.5 times applicable federal test procedure (FTP) standards). It is important to note that the OBD does not typically measure the emission levels in the exhaust gases directly. In general, the effect of system failure on emission levels is determined in the laboratory; the job of the OBD engineers is to help assess the condition of each monitored system with available signals, under laboratory emission testing, and develop monitoring algorithms that interpret the set of available signals as a sign of the monitored system's condition and the corresponding impact on emission levels.

Nonthreshold monitoring covers the majority of systems and involves checking for function and rational component performance along with electrical checks for signals that compose the OBD system. This includes monitoring of certain engine and aftertreatment components for total failure, ability to achieve a designated command target, response rate to reach the specified target, circuit continuity, voltage, current, and other characteristics for each separate system.

The monitoring strategies for both threshold and nonthreshold monitoring must be designed to detect problems, and at the same time, avoid giving either false passes or false malfunction indications. Monitoring is expected to occur under normal driving conditions for in-use vehicles; it also has to be reproducible under specific testing conditions. Some signals can be monitored continuously (e.g., circuit continuity), but others require that manufacturers define the conditions needed for the monitoring test to occur (e.g., minimum exhaust gas temperatures for catalyst light-off).

Table 2 presents an overview of the main OBD monitoring requirements for the studied programs. The table shows which vehicle systems are monitored for failures that can result in emission levels that exceed OTL and for functionality failures such as electrical circuit continuity or an actuator response. For detailed information we recommend the reader search within the corresponding regulatory documents listed in the References section of this document (CCR, 2013; MOE, 2015; UNECE, 2015).

The monitoring requirements for the California and Korea programs are much wider in scope and greater in stringency than those under the European program. For example, misfire detection for gasoline vehicles must take place under a much wider speed/load range in the California and Korean requirements compared to those for Europe. Also, cold start strategies, which are often present on vehicles certified to stringent emission standards to more quickly bring the catalyst system up to operating temperature, must be monitored under California OBD II, but are not covered by the European program. Under the European program, the monitoring conditions for most emission related systems are left exclusively to the manufacturer, as can be inferred from the minimal regulatory language, compared to the other two programs, and the fact that the requirements for many systems are grouped under broad category of "other emission control systems."

Table 2. Summary of OBD monitoring requirements for gasoline engines

System	California (CCR, 2013)	Korea (MOE, 2015)	Europe (UNECE, 2015)
1. Catalyst	Conversion capability linked to OTLs for nonmethane organic gas (NMOG) and NO_x	Conversion capability linked to OTLs for NMOG and NO_x	Conversion capability linked to OTLs for NMHC and NO_x
2. Heated catalyst monitoring	Monitor for proper heating correlated to OTLs		Monitor for proper heating correlated to OTLs
3. Misfire monitoring	Monitor for misfire causing: • catalyst damage and • excess emissions Continuous monitoring over full speed/ load range and correlated to OTLs	Monitor for misfire causing: • catalyst damage and • excess emissions Continuous monitoring over full speed/load range and correlated to OTLs	Euro 6-2 requires monitoring over most common speeds/ loads OTL monitoring
4. Evaporative system monitoring	• Verify purge flow from the evaporative system • Monitor the complete evaporative system for vapor leaks to the atmosphere 0.02"/0.5mm	• Verify purge flow from the evaporative system • Monitor the complete evaporative system for vapor leaks to the atmosphere 0.04"/1.0mm	Requires monitoring of purge control valve for circuit continuity Vapor leakage is not monitored
5. Secondary air system monitoring	• Monitor proper functioning of the air delivery system • OTL monitoring	• Monitor proper functioning of the air delivery system • OTL monitoring	Requires monitoring under "other emission control systems" • OTL monitoring
6. Fuel system monitoring	• OTL monitoring	• OTL monitoring	Requires monitoring under "other emission control systems" • OTL monitoring
	CARB also requires an emission correlated air/fuel ratio cylinder imbalance monitor (AFIM)		
7. Exhaust gas sensor monitoring	• OTL monitoring for primary and secondary sensors • Monitor for performance as a monitoring device (e.g., for catalyst monitoring) • Functionality monitoring (voltage, amplitude) • Monitor for sensor's heating functions	• OTL monitoring for primary and secondary sensors • Functionality monitoring (voltage, amplitude) • Monitor for sensor's heating functions	• OTL monitoring
8. Exhaust gas recirculation (EGR) system monitoring	OTL for high and low EGR faults • Functionality monitoring Monitor the output voltage, activity, response rate, and any other parameter which can affect emissions	OTL for high and low EGR faults • Functionality monitoring Monitor the output voltage, activity, response rate, and any other parameter which can affect emissions	Requires monitoring under "other emission control systems" • OTL monitoring
9. Positive crankcase ventilation (PCV) monitoring	Monitor for disconnection between key components	Monitor for disconnection between key components	Not monitored
10. Engine cooling system monitoring	Monitoring thermostat for proper operation and engine coolant temperature (ECT) sensor for circuit continuity, out-of-range, and rationality faults.	Monitoring thermostat for proper operation and ECT sensor for circuit continuity, out-of-range, and rationality faults	Monitoring of the ECT sensor for circuit continuity but does not require monitoring of the thermostat
11. Cold start emission reduction strategy monitoring	OTL monitoring Monitoring of applicable components (e.g., engine idle speed control and spark retard), for proper function while the control strategy is active	OTL monitoring Monitoring of applicable components, e.g., engine idle speed control and spark retard, for proper function while the control strategy is active	Not monitored

System	California (CCR, 2013)	Korea (MOE, 2015)	Europe (UNECE, 2015)
12. A/C system component monitoring	OTL for off-idle fuel and spark control strategies	OTL for off-idle fuel and spark control strategies	Not monitored
13. Variable valve timing and/or control (VVT) system monitoring	OTL emission correlated monitor for target error and/or slow response	OTL emission correlated monitor for target error and/or slow response	Requires monitoring under "other emission control systems" • OTL monitoring
14. Direct ozone reduction (DOR) system monitoring	Functional or OTL monitoring depending on NMOG credit received.	Not monitored	Not monitored
15. Comprehensive component monitoring	OBD monitor for malfunction of any electronic powertrain component/ system interact with engine control units (ECU) and that affect emission or is used as part of a diagnostic strategy for another component that is required to be monitored per the OBD regulation Diagnosis of a component if any failure mode causes a measurable increase in emissions, or impacts another OBD monitoring strategy Manufacturers would determine those components and are approved by the executive officer/adminstrator	OBD monitor for malfunction of any electronic powertrain component/system interact with ECUs and that affect emission Diagnosis of a component if any failure mode causes a measurable increase in emissions Manufacturers would determine those components and are approved by the administrator	• OTL monitoring • Monitor for circuit continuity **Examples of systems not covered by Euro 6 OBD:** • Customer operated driving mode inputs ("Sport", "Touring", "Eco", etc.) • Transmission sensors and actuators
16. Other emission control or source system monitoring	For other emission control or source systems the manufacturer should submit a plan for executive officer approval of the monitoring strategy, malfunction criteria and monitoring conditions prior to vehicle sale		Requires diagnosis if any failure mode increases emissions above the thresholds Monitor for circuit continuity

2.4 OBD THRESHOLD LIMITS

Table 3 presents a summary of the OTLs currently in place and most relevant to this comparison across programs. The comparison covers gasoline and diesel OTLs. Note that the biggest difference between the Californian and the European OTL definitions is that EOBD defines OTL for a handful of emission control systems and the others are implicitly defined as "other emission control systems," while CARB provides OTL per system for most systems.

The OTLs presented here are those that currently apply to gasoline and diesel vehicles, i.e., outdated OTLs are not presented here. Under the CARB OBD program for gasoline vehicles the current OTLs started in 2009; for diesel vehicles the current OTLs apply since 2010 for most sensors and engine-out emission control systems, and since 2013 for aftertreatment systems.

For the European program, the OTLs presented here cover only passenger cars (vehicle category M1). Because the European commission constantly updates the emission standards and the OBD limits, we decided to show here only the most stringent ones. These OBD limits, for Euro 6c, will be applied for type approval in September 2017 and for all new vehicles in September 2018.

Note that the CARB OBD II program and the KOBD program have different OTLs for different vehicle classes and by the subset certification level (LEV, ULEV, SULEV). In general, passenger cars and light trucks that are certified as SULEV II compliant have one set of OTLs, while all other vehicles are grouped with more stringent OTLs. However, because the SULEV II standards are more stringent, the emissions increase for MIL activation is still lower for SULEV II than the other California standards.

As an example, under the Californian and Korean OBD programs MIL would activate for a failure on a catalyst that would lead to emissions above 1.75 times the standard (1.75 x 43 mg/km = 75 mg/km). Under the Euro 6-2 OBD program, only a failure leading to emissions greater than 1.5 times the standard (1.5 x 60 mg/km = 90 mg/km) would activate the MIL.

Table 3. Summary of OBD Threshold values for gasoline and diesel vehicles

Monitoring Area	California (2013)	Korea	Europe (Euro 6-2, 2017)
Spark ignition (gasoline)	NO_x std: 43 mg/km NMOG std: 56 mg/km	NO_x std: 43 mg/km NMOG std: 56 mg/km	NO_x std: 60 mg/km NMHC std: 68 mg/km
Catalytic converter	• PC/LDT SULEV II: 2.5 x NO_x FTP std 2.5 x NMOG FTP std • All other vehicles: 1.75 x NO_x FTP std 1.75 x NMOG FTP std	• PC/LDT SULEV II: 2.5 x NO_x FTP std 2.5 x NMOG FTP std • All other vehicles: 1.75 x NO_x FTP std 1.75 x NMOG FTP std	2.5 x NMHC NEDC std 1.5 x NO_x NEDC std
Engine misfire[a]	1.5 x all FTP stds	1.5 x all FTP stds	1.9 x CO NEDC std 2.5 x NMHC NEDC std 1.5 x NO_x NEDC std PM[b]: 2.7 x PM NEDC std
Exhaust gas sensors[a]	1.5 x all FTP stds	1.5 x all FTP stds	
Secondary air[a]	1.5 x all FTP stds	1.5 x all FTP stds	Not explicit. These systems are covered under "other emission control systems components or systems connected to a computer" The OTLs are the same as those for engine misfire and exhaust gas sensors
Fuel systems[a]	1.5 x all FTP stds	1.5 x all FTP stds	
Exhaust gas recirculation (EGR)[a]	1.5 x all FTP stds	1.5 x all FTP stds	
Variable valve timing (VVT)[a]	1.5 x all FTP stds	1.5 x all FTP stds	
Other emission related systems	1.5 x all FTP stds	1.5 x all FTP stds	
Air conditioning [a]	1.5 x all FTP stds	1.5 x all FTP stds	—
Evaporative system	Leakage equivalent to 0.02" orifice	Leakage equivalent to 0.04" orifice	Not monitored
Compression ignition/diesel			
DOC, DPF, LNT and SCR	1.75 x NMHC or CO FTP std 1.75 x NO_x FTP std 1.75 x PM FTP std	Similar to Euro 6-1 CO: 1750 mg/km 3.5 x CO NEDC std HC: 290 mg/km 3.2 x HC NEDC std NO_x 180 mg/km 2.25 x NO_x NEDC std PM: 25 mg/km 5.6 x PM NEDC std	Euro 6-2 2.5 x CO NEDC std 3.2 x NMHC[c] NEDC std 1.75 x NO_x NEDC std 2.7 x PM NEDC std
Upstream air-fuel ratio sensor, VVT, fuel system monitor, downstream sensors, NO_x and PM sensors, EGR system monitor, boost pressure monitor, cold start emission reduction strategy[a]	1.50 x NMHC or CO FTP std 1.50-1.75 x NO_x FTP std 2.0 x PM FTP std	Not explicit. Assumed as same as above. These systems are covered under "other emission control systems components or systems connected to a computer"	Not explicit. Assumed as same as above. These systems are covered under "other emission control systems components or systems connected to a computer"
Misfire monitor	1.50 x NMHC or CO FTP std 1.50 x NO_x FTP std 1.50 x PM FTP std	—	—

Notes:
[a] Under CARB regulations: for PC/LDT SULEV II, a threshold of 2.5x is allowed.
[b] PM standards apply to GDI vehicles only. Port fuel injected gasoline vehicles do not have PM standards.
[c] There is no NMHC emission standard for diesel vehicles in Europe, only HC+NO_x and NO_x, so the difference between these two standards is taken here for providing some level of comparison among programs.

2.5 DURABILITY REQUIREMENTS

All programs present durability requirements that are attached to the vehicle useful life. The European program requires that all vehicles be equipped with an OBD system designed, constructed, and installed to identify malfunctions over the entire life of the vehicle. The California program also requires the OBD to be designed to operate, without required scheduled maintenance for the actual life of the vehicle, and to not be deactivated by software or design. Note that requirements for OBD thresholds compliance cover only the legal useful life of the vehicle (193,000 km). The Korean regulation is similar to the Californian one.

2.6 COMMUNICATION PROTOCOLS

California, Korea and the latest European OBD regulations mandate the standardization of communication protocols as well as the connectors for OBD scan tools and the scan tools. Without standardized protocols, the market would have to develop OBD scan tools for each manufacturer; this would make inspection and maintenance programs that are based on OBD information a very complex task to carry out due to the need for having OBD scanners by manufacturer.

All OBD systems reference the same set of Society of Automotive Engineers (SAE) and International Standardization Organization (ISO) standards for definitions, connectors, scan tools, diagnostics trouble codes, communication protocols and others. The OBD II system is standardized in ISO 15031 and consists of seven parts. In general, ISO 15031 is harmonized with the SAE standardization and there are only minor deviations between the related ISO and SAE documents. The SAE J1979/ISO 15031-5 set includes the communication between the vehicle's OBD systems and test equipment implemented across vehicles within the scope of the legislated emissions-related OBD. SAE J1979/ISO 15031-5 intend to harmonize U.S. federal, California, and European OBD program standards (Euro 5 and Euro 6) (SAE, 2014; ISO, 2015).

An OBD compliant vehicle has to provide a standardized connector that enables communication with an external scan tool. The connector design is set by the Standard SAEJ1962. Table 4 presents the SAE/ISO requirements on OBD communication protocols.

Table 4. OBD standardization requirements

Specification	Standard
Scan tool	SAE J1978
Connector	SAE J1962
Communication protocol	ISO 15765-4 (CAN) SAE J1979/ISO 15031-5 set includes the communication between the vehicle's OBD systems and test equipment implemented across vehicles within the scope of the legislated emissions-related OBD

3. PROVISIONS ON ANTI-TAMPERING AND FRAUDULENT PASSING I/M TESTING

There are challenges that prevent the OBD system from achieving full potential via I/M programs, with DTC clearing, ECU tampering, and fraudulent inspections being the primary issues. DTC clearing occurs more frequently as vehicle owners prefer to delete the code instead of fixing the issue that is causing the MIL to be active. ECU tampering is less frequent as it involves a reflashing of the vehicle engine control module to change the performance of the engine (i.e., increasing fueling rates for higher power output) or tampering to defeat the OBD system. Other forms of tampering observed in diesel vehicles involve removing the DPF from the exhaust pipe and altering the OBD system to avoid DTCs.

Regulators and manufacturers have developed and incorporated provisions that help reduce the incidence fraudulent passing inspection via code clearing and ECU tampering. These tools are permanent DTCs, I/M readiness bits and the calibration identification number (CAL ID) and calibration verification number (CVN)

3.1 PERMANENT DTC

Permanent DTCs are intended to prevent passing annual I/M testing by deleting the trouble codes. Upon confirming that a malfunction is present, trouble codes are stored in the memory in one of the vehicle's control modules and the MIL is illuminated. Drivers facing an active MIL before annual vehicle inspection may be motivated to solve the problem by deleting the trouble code and turning off the MIL via code clearing practices, rather than fixing the root cause of the MIL activation with its associated repair costs. Having the technical capacity built into the vehicle's control modules to store the OBD trouble codes until the malfunction is fixed is a key component of modern OBD systems and fundamental for robust I/M programs.

CARB and Korea have specific requirements for identification and storage of permanent DTCs. China 5 and Euro 6-2 OBD have similar requirements, but there are some differences on permanently storing DTCs. CARB and Korea have established clear requirements for storing DTCs in the nonvolatile random access memory (NVRAM), but this is not covered within the Euro 6-2 regulation. This provides CARB and Korea OBD with better protection against clearing DTCs without repairs being made and provides much better technical support for an I/M program based on OBD data. The permanent DTCs required by the CARB regulation remain in memory until the monitor that stored the fault code passes and turns off the MIL. A permanent DTC in memory without MIL illumination provides the inspector with the information that the vehicle had detected a malfunction before fault information was cleared and the diagnostic that detected the malfunction has not subsequently passed and judged the malfunction to be no longer present.

An alternative to DTC requirements for China is the adoption of a system that stores the codes outside the vehicle by capturing the OBD information wirelessly and more frequently. The collection system can be located at a roadside station, or via local cellular networks. This type of system is known as Remote I/M, or Continuous I/M.

3.2 I/M READINESS BITS

Readiness bits were CARB's first attempt to address fraudulently passing I/M. With OBD I, many drivers were found to be clearing codes by disconnecting batteries just before going to the I/M station so they could pass the inspection, even though they had a malfunction. By disconnecting the battery the control module in charge of storing the codes loses power, clearing all the stored data. Intending to address this issue, CARB added I/M readiness bits to the second phase of the OBD regulation, OBD II.

The readiness code is a set of 10 bits, each of them corresponding to one monitored system. OBD II has readiness bits for certain key monitors that take the most time to be ready for OBD testing after the battery has been disconnected or a DTC cleared. If the codes are cleared or the battery is disconnected, the readiness bits are immediately set to "Not Ready," and the vehicle will not pass I/M because the OBD system is not ready to provide valid diagnostic information. After the vehicle has been driven enough that all or nearly all of the monitors with readiness bits have completed, the corresponding bits are set to ready and the vehicle is ready for inspection.

Readiness codes have been successful at preventing fraudulent passing of I/M tests, but this approach also has some challenges. First, if repair work is conducted at a date close to the I/M testing date, the readiness codes might not be immediately ready for the vehicle to be inspected as some OBD systems require a certain amount of driving to enable monitors and either set readiness or detect a malfunction that wasn't properly repaired. Local authorities have some level of control over exceptions to some readiness bits for such cases by implementing readiness exception rules.

Permanent DTCs and readiness codes are complementary measures. If codes are cleared or the battery is disconnected, the permanent DTC must be retained in NVRAM. The permanent DTC can only be erased by the OBD system itself when the diagnostic completes and passes. As an example, a I/M inspector facing a vehicle with a catalyst monitor readiness set as "not ready," but with no permanent DTC for catalyst monitor, could still permit the vehicle to undergo inspection by relying on the permanent DTC information.

3.3 CALIBRATION IDENTIFICATION AND CALIBRATION VERIFICATION NUMBER

The CAL ID and CVN are tools that CARB and Korea added to the OBD II regulation to prevent and detect tampering. During annual vehicle inspection, the CVN is downloaded from the vehicle and compared to a broad national CAL ID database maintained by the government of manufacturer authorized CAL ID/CVN combinations. If someone accesses the engine control module (ECM) and tampers with the original control setup by changing fuel and spark calibrations to increase horsepower or turn off a diagnostic, the CVN will be altered and it will not match the one given by the manufacturer to the inspection authority. The CVN is an effective tool for discovering tampering.

Manufacturers have been required to incorporate CAL IDs and CVNs since model year 2005 in California and since 2008 at the U.S. federal level. The responsibility of the manufacturers is to provide the right CAL ID/CVN database to regulators; the responsibility of regulators is to make sure the CAL ID/CVN database is constantly updated and that it is distributed across all I/M stations. The database must be 100% accurate and secure to be effective.

The main challenges to the effectiveness of CAL IDs/CVNs are that (a) there is anecdotal evidence of incorrect numbers provided by the OBD supplier to the vehicle manufacturer (Ferris et al., 2015) and that (b) it is possible reflash the vehicle ECU with the correct production ECM before the I/M testing and then replace it with the tampered version after the I/M is passed (Ferris et al., 2015). This second challenge can be addressed via remote OBD by reading the CAL ID/CVN wirelessly and frequently.

Europe has adopted standardized CAL IDs for the Euro 6 OBD program.[3] According to the EU regulation, the software CAL ID should be made available through the serial port on the standardized data link connector. There is no mention in the European OBD regulation of CVN requirements.

3 Within the European regulation the calibration identification number is mentioned in section 6.5.1.5 of Appendix 1 of Annex 11 to UN/ECE Regulation No 83.

4. CERTIFICATION AND CONFORMITY OF PRODUCTION PROCESS FOR MANUFACTURERS

To deliver on the promise of environmental and health benefits from new vehicle standards, an effective vehicle compliance and enforcement program has to be in place to ensure that regulations for new and in-use vehicles are effectively implemented. This subsection summarizes critical elements of the vehicle compliance and enforcement programs for OBD systems in the United States, the European Union and Korea.

The U.S. vehicle compliance program is by far the most comprehensive and far-reaching compliance program in the world. Before the Clean Air Act (CAA) was passed in 1970, the United States had a vehicle compliance program that only covered prototypes for new vehicle certification. The CAA changed that, adding authority for the EPA to ensure that all vehicles coming off the assembly lines meet standards. It also authorized the EPA to hold manufacturers responsible for vehicles meeting standards throughout their useful lives, provided that customers properly maintain them. Lastly, the CAA required manufacturers to warrant individual emission control components on vehicles to protect consumers. Over the years, the compliance program has grown and evolved from one that focused mainly on verifying that both prototype and new production vehicles complied with standards to one that places strong emphasis on in-use testing and durability to ensure that emission standards are met over the useful life of a vehicle. The development and evolution of OBD systems also required developing special regulatory elements for compliance and enforcement of these systems.

4.1 TYPE-APPROVAL/CERTIFICATION OF OBD SYSTEMS

Before a new vehicle receives official approval for sale within the markets in question, the manufacturer is required to demonstrate that the OBD system installed in the new vehicle meets certain type-approval or certification requirements. In general terms this involves carrying out tests that show that the OBD system responds as expected, i.e., detects a malfunction and activates the MIL once simulated failures are induced on the vehicle. The OBD demonstration verifies that the emission threshold monitors will illuminate the MIL before exceeding the emission thresholds. This demonstration testing is usually done several months before production.

CARB and Korea require OBD demonstration testing. CARB requires all manufacturers to perform demonstration emission testing to confirm emission correlated monitors meet requirements.

CARB may also conduct confirmatory testing of same vehicle configuration with manufacturer support. Most manufacturers have had confirmatory testing (Ferris et al., 2015).

CARB and Korea require submission of comprehensive OBD documentation every year; review and approval takes on average 60 to 120 days. In Korea, submission is just for new types of vehicles, not those currently in production. During this process of submitting technical documents that confirm the proper operation of OBD systems, some level of discussion and request for further information is expected. According to industry experts, most of CARB's questions are oriented at further explaining the OBD monitoring strategies and details on testing results; in some cases the requests cover unclear documentation (Ferris et al., 2015).

4.1.1 CARB OBD II

Monitoring system demonstration requirements for certification
The certification process in California, and to some extent in Korea, requires that manufacturers submit emission test data from one or more demonstration test vehicles. Prior to submitting any applications for certification for a model year, a manufacturer should notify the executive officer of the test groups planned for that model year. The executive officer will then select the test group(s) that the manufacturer should use as demonstration test vehicles to provide emission test data and demonstrate OBD system performance.

A manufacturer certifying one to five test groups in a model year should provide emission test data from a test vehicle from one test group. A manufacturer certifying six to 15 test groups in a model year should provide emission test data from test vehicles from two test groups. A manufacturer certifying 16 or more test groups in a model year should provide emission test data from test vehicles from three test groups.

For the test vehicles, a manufacturer should use a certification durability vehicle, a test vehicle with a representative high mileage, or a vehicle aged to the end of the full useful life through a CARB approved durability procedure.

The testing of OBD systems requires that the manufacturer perform single-fault testing based on the applicable FTP test with the following components/systems set at their malfunction criteria limits as determined by the manufacturer.

Required testing for spark ignited vehicles
The components to be tested in California and Korea are:

Oxygen sensors: The manufacturer should perform a test with all primary oxygen sensors used for fuel control operating at the malfunction criteria level. In Korea, two tests are performed. The first test involves testing oxygen sensors with normal output voltage but with a response rate deteriorated to the malfunction criteria limit. The second test includes testing with oxygen sensors possessing output voltage at the malfunction criteria limit.

EGR system: The manufacturer should perform a test for low flow. Same requirements in Korea.

VVT system: The manufacturer should perform a test for target error limit and slow response. Same requirements in Korea.

Fuel system: For vehicles with adaptive feedback based on the primary fuel control sensor(s), the manufacturer should perform a test with the adaptive feedback based on the primary fuel control sensor(s) at the rich limit(s) and a test at the lean limit(s). For vehicles with feedback based on a secondary fuel control sensor(s), the manufacturer should perform a test with the feedback based on the secondary fuel control sensor(s) at the rich limit(s) and a test at the lean limit(s). Same requirements in Korea.

Misfire: The manufacturer should perform a test at the malfunction criteria limit. Same requirements in Korea.

Secondary air system: The manufacturer should perform a test at the low flow limit. Same requirements in Korea.

Catalyst system: The manufacturer should perform a test using a deteriorated catalyst system. Same requirements in Korea.

Other systems: The manufacturer should conduct demonstration tests for all other emission control components designed and calibrated to an emission threshold malfunction criteria (OTLs). Not specified under the Korean OBD program.

Required testing for compression ignition (diesel) vehicles
The components to be tested in California and Korea are:

NMHC catalyst: The manufacturer should perform a separate test for each monitored NMHC catalyst that is used for a different purpose (e.g., oxidation catalyst upstream of a PM filter, NMHC catalyst used downstream of an SCR catalyst). The catalysts being evaluated should be deteriorated to the applicable malfunction criteria.

NO_x catalyst: The manufacturer should perform a separate test for each monitored NO_x catalyst (e.g., passive lean NO_x catalyst or SCR catalyst). The catalysts being evaluated should be deteriorated to the applicable malfunction criteria.

Fuel system: The manufacturer should perform a separate test for each applicable malfunction limit established by the manufacturer for the fuel system parameters (e.g., fuel pressure, injection timing, injection quantity).

Exhaust gas sensor: The manufacturer should perform a test for each exhaust gas sensor parameter, including air-fuel ratio sensors, NO_x sensors, and PM sensors.

EGR system: The manufacturer should perform a test at each flow, slow response, and cooling limit calibrated to the malfunction criteria for low/high flow malfunction, slow response and EGR cooler performance.

Boost pressure control system: The manufacturer should perform a test at each boost, response, and cooling limit calibrated to the malfunction criteria for over and under boost, slow response and charge air undercooling.

NO_x adsorber: The manufacturer should perform a test using a deteriorated NO_x adsorber. The manufacturer should also demonstrate that the OBD II system detects a NO_x adsorber malfunction when the NO_x adsorber is completely removed.

PM filter: The manufacturer should perform a test using a PM filter(s) deteriorated to each applicable malfunction criterion for filtering performance, higher than specified regeneration frequency and NMHC conversion. The manufacturer should also demonstrate that the OBD II system will detect a PM filter malfunction when the filter is removed from the filter housing.

Cold start emission reduction strategy: The manufacturer should perform a test for each component of the cold start emission reduction control strategy the failure or deterioration of which would cause a vehicle's NMHC, CO, NO_x, or PM emissions to exceed the respective OTLs.

VVT system: The manufacturer should perform a test at each target error limit and slow response limit calibrated to the malfunction criteria from target error deviations and slow response.

OBD testing protocol
The testing of OBD systems under both the CARB and Korea OBD program consists of the following phases:

a) The manufacturer should set the system or component on the test vehicle for which detection is to be tested prior to conducting the applicable preconditioning cycle.

b) Preconditioning can be performed on an applicable cycle (FTP, SET, or unified cycle) prior to conducting each of the above emission tests.

c) The test vehicle should be operated over the applicable cycle to allow for the initial detection of the tested system or component malfunction.

d) The test vehicle should then be operated over the applicable exhaust emission test.

Alternatively, at the request of the manufacturer and approval by the executive officer, malfunctions of one or more components may be electronically simulated during testing according to specific requirements.

Evaluation protocol:
Under both the CARB and Korea OBD program, for all tests conducted, the MIL should illuminate upon detection of malfunction before the end of the first engine start portion of the exhaust emission test (or before the hot start portion of the last unified cycle, if applicable). If the MIL illuminates prior to emissions exceeding the applicable malfunction criteria, no further demonstration is required. If the MIL does not illuminate when the systems or components are set at their limit(s), the criteria limits or the OBD II system is not acceptable. Special considerations are given for selected systems tested.

4.1.2 Korea OBD

Monitoring system demonstration requirements for certification
Korean OBD requirements are similar to those under the CARB OBD II program. The main difference is that the Korean OBD program for gasoline vehicles does not have explicit testing requirements for “other systems.” Also, the requirements for diesel vehicles are closer to those of Europe because the Korean emission standards for diesel vehicles follow the European pathway, rather than that of the United States.

Required testing for spark ignited vehicles
The requirements are similar to Californian OBD II, as previously presented.

Required testing for compression ignition (diesel) vehicles
The requirements are similar to European OBD program requirements for diesel vehicles.

Catalyst (DOC): replacement of the catalyst with a deteriorated or defective catalyst or electronic simulation of such a failure that results in emissions exceeding any of the limits.

Diesel particulate filter (DPF): total removal of the particulate trap or replacement of the particulate trap with a defective particulate trap that results in emissions exceeding any of the limits.

Fuel systems: disconnection of any fueling system electronic fuel quantity and timing actuator that results in emissions exceeding any of the limits.

Emission related components connected to ECU: disconnection of any other emission-related power train component connected to a computer that results in emissions exceeding any of the limits.

EGR system: malfunctions of the EGR flow and cooling system.

OBD testing protocol
The Korean OBD testing protocol for gasoline vehicles is identical to that of the Californian program, as previously presented.

Evaluation protocol:
The Korean OBD Evaluation protocol for gasoline vehicles is identical to that of the Californian program, as previously presented.

4.1.3 Euro 6 OBD

The European program also has its own specific requirements for OBD type approval. The procedure describes a method for checking the function of the OBD system installed on the vehicle by failure simulation of relevant systems in the engine management or emission control system. Different failure modes are tested for gasoline and diesel vehicles. It also sets procedures for determining the durability of OBD systems.

The manufacturer is required to make available the defective components and/or electrical devices which would be used to simulate failures. When the vehicle is tested with the defective component or device fitted, the OBD system is approved if the MIL is activated. The OBD system is also approved if the MIL is activated below the OBD threshold limits. One remarkable aspect of OBD testing for type approval is that manufacturers are required to test no more than four failures for type approval.

The testing of OBD systems consists of the following phases:

a) Simulation of malfunction of a component of the engine management or emission control system.
b) Preconditioning of the vehicle with a simulated malfunction over preconditioning protocols.
c) Driving the vehicle with a simulated malfunction over the test cycle and measuring the vehicle emissions.
d) Determining whether the OBD system reacts to the simulated malfunction and indicates malfunction in an appropriate manner to the vehicle driver.

Alternatively, at the request of the manufacturer, malfunctions of one or more components may be electronically simulated during testing according to specific requirements.

Manufacturers may request that monitoring take place outside the test cycle if it can be demonstrated that monitoring during conditions encountered during the test cycle would impose restrictive monitoring conditions when the vehicle is used in service.

Failure modes to be tested for spark-ignited vehicles
The MIL should activate before the end of this test under any of the conditions listed below:

- **Catalyst**: replacement of the catalyst with a deteriorated or defective catalyst that results in emissions exceeding any of the limits.
- **Engine misfire**: engine misfire conditions according to the conditions for misfire monitoring (see 3.3.3.2. of Annex 11 to UN/ECE Regulation No 83).
- **Oxygen sensor**: replacement of the oxygen sensor with a deteriorated or defective oxygen sensor or electronic simulation of such a failure that results in emissions exceeding any of the limits.
- **Emission-related components connected to ECU:** electrical disconnection of any other emission-related component connected to a power-train management computer (if active on the selected fuel type) that results in emissions exceeding any of the limits.
- **Evaporative emissions**: electrical disconnection of the electronic evaporative purge control device.

Failure modes to be tested for compression-ignited vehicles
The MIL should activate before the end of this test under any of the conditions listed below:

- **Catalyst (DOC):** replacement of the catalyst with a deteriorated or defective catalyst that results in emissions exceeding any of the limits.
- **Diesel particulate filter (DPF):** total removal of the particulate trap or replacement of the particulate trap with a defective particulate trap that results in emissions exceeding any of the limits.
- **Fuel systems**: disconnection of any fueling system electronic fuel quantity and timing actuator that results in emissions exceeding any of the limits.
- **Emission related components connected to ECU:** disconnection of any other emission-related power train component connected to a computer that results in emissions exceeding any of the limits.
- **EGR system**: malfunctions of the EGR flow and cooling system.

The reader should note that the SCR system is not explicitly covered as part of the OBD type-approval testing requirements.

4.1.4 Summary

Table 5 shows that Californian and Korean OBD programs require a much more robust demonstration testing than that from the Euro 6-2 OBD requirements. The OBD systems covered under the Euro 6-2 regulations for gasoline systems are misfire, catalyst, O_2 sensor, and evaporative system purge. The requirements in California are much more extensive and are not limited to only four failures, as is the case of EU demonstration testing. Korean requirements for gasoline vehicles are very similar to CARB requirements, leaving out only the Other Systems testing requirements; for diesel vehicles, the Korean requirements are similar to those of the European program.

Table 5. List of emission related components that are required to be tested under each program

Certification requirement	CARB OBD II	KOBD	EOBD
Component testing for gasoline cars	Oxygen sensors EGR system VVT system Fuel system Misfire Secondary air system Catalyst system Other emission-related systems	Oxygen sensors EGR system VVT system Fuel metering Misfire Secondary air system Catalyst system Heated catalysts (not used in vehicles)	Catalyst Engine misfire Oxygen sensor Other emission-related components Evaporative purge system
Component testing for diesel cars	NMHC catalyst NO_x catalyst Fuel system Exhaust gas sensor EGR system Boost pressure control system NO_x adsorber PM filter Cold start emission reduction strategy VVT system	DOC DPF Fuel systems Other emission-related components EGR system	DOC DPF Fuel systems Other emission-related components EGR system

4.2 PRODUCTION VEHICLE EVALUATION TESTING

Production vehicle evaluation (PVE) testing is performed on production vehicles, which is different from preproduction conformity demonstration testing and verification. This type of testing intends to make sure that the OBD system is functioning properly in production software (i.e., without software bugs) with production hardware. PVE covers three main aspects of OBD: PVE – communication protocols, PVE – verification of monitoring requirements, and PVE – verification and reporting of in-use monitoring performance. The Korean and Euro 6 OBD programs require only the latter.

PVE – *verification of standardized requirements* confirms proper communication with a generic OBD scan tool. Manufacturers perform this testing every model year on one production vehicle from every unique OBD calibration within two months of the start of normal production for that calibration. Manufacturers may request executive officer approval to group multiple calibrations together and test one representative calibration per group. Typically, calibrations are grouped by communication characteristics and one vehicle is tested per OBD group. A report is submitted to CARB.

The testing confirms proper OBD communication through the generic scan tool of the following information:

- Properly establish communications between all emission-related onboard computers and any SAE J1978 scan tool
- Current readiness status from all onboard computers

- The MIL command status while the MIL is commanded off and while the MIL is commanded on
- All data stream parameters in accordance with SAE J1979
- The CAL ID, CVN, and VIN (if applicable) in accordance with SAE J1979
- An emission-related fault code (permanent, confirmed, and pending) in accordance with SAE J1979 when a fault is introduced

Korea, China 5 and Euro 6-2 do not require PVE communication testing.

PVE – v*erification of monitoring requirements* confirms the ability of the OBD II system on the selected production vehicle to detect a malfunction, illuminate the MIL, and store a confirmed fault code. The PVE verification testing is done on real production vehicles and includes all diagnostics that can practically be tested without damaging the vehicle. The emission threshold diagnostics are retested, excluding emission tests, to make sure that no errors are present in production software.

In practical terms it requires that the manufacturer install a fault while avoiding damaging the vehicle. For example, manufactures can install faulty components into the vehicle for PVE verification testing but generally cannot test for faults that would occur inside a control module. A report is presented covering the method used to induce the malfunction, the MIL illumination status, and the confirmed fault codes.

Korea and Euro 6-2 do not require PVE verification of monitoring testing.

PVE – *verification and reporting of in-use monitoring performance* testing covers IUMPR data. Manufacturers are required to collect and report in-use monitoring performance data representative of every test group certified by the manufacturer and equipped with in-use monitoring performance tracking software. These data provide information on how frequently OBD monitors are functioning on the road by the vehicle operators. CARB requires manufacturers to collect and report IUMPR data within 12 months after introduction into commerce (start of sale). Test groups with similar characteristics may be combined and data collected from 15 vehicles per group; manufacturers can request the testing of fewer vehicles to CARB under limited circumstances.

Euro 6-2 has similar PVE IUMPR requirements. An audit of in-service conformity is conducted by the approval authority on the basis of information supplied by the manufacturer. The manufacturer demonstrates to the approval authority that the statistical conditions that apply to the IUMPR concept are satisfied for vehicles manufactured in a given calendar year for all monitors required to be reported by the OBD system according to Euro 6 OBD IUMPR monitoring requirements and not later than 18 months after the end of a calendar year.

The Euro 6 OBD requirements are deemed to be met for a particular monitor if, for all vehicles of a particular OBD family manufactured in a particular calendar year, the following statistical conditions hold:

a) The average IUMPR is equal or above the minimum value applicable to the monitor

b) More than 50% of all vehicles have an IUMPR equal to or above the minimum value applicable to the monitor

Korea requires only submission of development data at time of certification.

A summary of PVE testing requirements by program is presented in Table 4. The Californian OBD II program has the most detailed testing requirements among the three evaluated programs. There are no PVE requirements for communication standardization and monitoring under the Korean and European programs.

Table 4. Summary of production vehicle evaluation (PVE) testing requirements

PVE Requirements	CARB OBD II	KOBD	EOBD
PVE - Verification of standardized requirements	Manufacturers confirm proper communication with a generic OBD scan tool It occurs within two months of the start of production One vehicle is tested per unique calibration unless further grouping is approved by CARB	Not required	Not required
PVE – Verification of monitoring requirements	Manufactures confirm the ability of the OBD II system to detect a malfunction, illuminate the MIL, and store a confirmed fault code It occurs during the first six months of the start of production Sample size is double the number of demonstration vehicles	Not required	Not required
PVE - Verification and reporting of in-use monitoring performance	Manufacturers are required to collect and report IUMPR data to authorities Data should be presented within 12 months of commercial introduction All 15 vehicles per representative grouping	Korea requires only submission of development data at time of certification	Manufacturers are required to collect and report IUMPR data to authorities Data should be presented within 18 months of commercial introduction The in-use conformity verification applies to 5% of the type approved OBD families

4.3 OBD DEFICIENCIES

Deficiencies are a flexibility given under the OBD programs to manufacturers to be able to certify their vehicles even while failing to meet one or more OBD requirements. As part of the requirements to obtain a certification or type approval with one or more deficiencies on a vehicle, the official conducts a review of the current OBD system in general and compares that to the full OBD requirements.

CARB and EU authorities grant certification with deficiencies provided that the following conditions are met:

» Good faith effort to meet the requirements in full

- Use of the best available monitoring technology
- Plan to come into compliance “as expeditiously as possible”

The program allows for deficiencies to be carried over for no more than two model years, and subject to authorities’ approval. Manufacturers must present a plan to comply and justify the time needed. The manufacturer progress toward correcting the deficiency is considered when extending the deficiency for one more year. Deficiencies may be granted retroactively within 6 months after start of production

OBD fines are levied on manufacturers that have three or more deficiencies or when one of the OBD monitoring deficiencies is completely missing from the program. Fines for OBD deficiencies, on a per-vehicle basis, are:

- $50 per deficiency for major monitors (e.g., EGR)
- $25 per deficiency for minor monitors (e.g., temperature sensor)
- Total fines are not to exceed $500 per vehicle
- Fines apply only to vehicles sold in California

Deficiencies are not allowed for the most serious issues. A serious issue can be defined as one where the malfunction would cause emissions two times above the OTL.

OBD issues are discussed with CARB throughout the certification and deficiencies process. Early negotiation occurs 6-9 months before production if during that timeframe the manufacturer realizes that the hardware is not adequate for compliance. The most typical situation is to identify the potential deficiency during the development testing, before the OBD demonstration testing. Potential deficiencies are rarely identified late during the OBD demonstration process, according to Ferris et al. (2015)

5. ENFORCEMENT

5.1 CALIFORNIA

California performs emission testing in its own chassis testing facilities for the enforcement of OBD II requirements. Upon request by the executive officer, the manufacturer makes available to the authorities all test equipment (e.g., malfunction simulators, deteriorated "threshold" components, etc.) necessary to determine the malfunction criteria. This testing covers major monitors subject to OBD II emission testing as previously defined. Further, the executive officer may develop threshold components and may conduct testing for compliance with any OBD II requirement.

The systems tested include, but are not limited to, aged "threshold" catalyst systems and computer equipment used to simulate misfire, oxygen sensor, fuel system, VVT system, and cold start reduction strategy system faults.

5.2 KOREA

The enforcement section within the KOBD regulation is similar in essence to the intention of the Californian regulation. According to the KOBD regulation, the Ministry of Environment can test the monitoring system in addition to manufacturer submitted data verification. For this type of enforcement testing, the manufacturer submits testing equipment and malfunction components relevant to the test. Systems that are found noncompliant with the regulation are deemed unacceptable. The language stops short of describing the consequences of a single system fault or the fate of the vehicle being tested.

5.3 EUROPE

In Europe, the in-use performance of vehicle emission systems, including OBD systems, is performed during in-service conformity checks. The manufacturer reports to the type-approval authority on warranty claims, warranty repair works and OBD faults recorded at servicing. The information shall detail the frequency and substance of faults for emissions related components and systems. Up to three vehicles are selected per vehicle family. The vehicle shall have been in service for at least 15 000 km or 6 months, whichever is later, and for no more than 100,000 km or 5 years, whichever is sooner.

If the European authority finds that the data provided by the manufacturer are unsatisfactory to prove the compliance of the systems the authority can perform the testing on its own. The in-use conformity checks cover the same testing used for conformity as presented in the previous chapter.

6. SUMMARY OVERVIEW OF OBD PROGRAMS

This section presents an overview comparing all components of the OBD programs across three regions (Table 5). It also includes a description of the changes in hardware that would be required when moving from Euro 5/China 5 to the most advanced Euro 6, KOBD and OBD II programs.

Table 5. Comparison of the main regulatory elements of the European, Korean and Californian OBD programs

OBD Requirement	Program comparison			Comments	Hardware changes required from Euro 5/China 5 OBD
	Euro 6-2	KOBD	CARB		
MIL and DTC – basic				Similar requirements	
Fuel consumption data				Provides access to cumulative fuel consumed, total distance traveled and other relevant data for CO_2 and fuel consumption policy design.	Increased EDU memory Capacity for saving data
DTC – permanent codes				Euro 6-2 OBD has no permanent DTC storage Very important to prevent I/M cheating	KOBD and CARB require nonvolatile RAM memory for storing permanent DTCs
Readiness bits				Similar requirements	
IUMPR				Similar requirements	
Emission thresholds				OBD II has the most stringent standards for gasoline and diesel vehicles KOBD has requirements for gasoline vehicles similar to CARB OBD II but the diesel requirements are similar to Euro 6-2	
Monitoring requirements					
Catalyst				Similar requirements	
Heated catalyst				Heated catalysts are not commercially used	
Misfire				OBD II and KOBD have an extensive list of misfire monitoring requirements CARB and Korea require continuous monitoring over full speed/load range to an emission correlated threshold Extreme operating regions more susceptible to fuel quality/early MILs	
Evaporative system				Euro 6-2 OBD checks for purge only; KOBD and OBD II check for that and leaks	KOBD and CARB require canister vent solenoid and fuel tank pressure sensor. Given that CARB has a more stringent leak threshold than Korea, there may be different hardware requirements
Secondary air system				Euro 6-2 monitors fuel system under "other ECs systems"	
Fuel system – basic				Euro 6-2 monitors Fuel system under "other ECs systems"	
Fuel system – AFIM				CARB also requires an emission correlated Air Fuel Imbalance Monitor (AFIM)	Manufacturers use special intake manifold designs, catalyst redesigns, and oxygen sensor location

OBD Requirement	Program comparison			Comments	Hardware changes required from Euro 5/China 5 OBD
	Euro 6-2	KOBD	CARB		
Exhaust gas sensors – O_2 sensors				Similar requirements	
EGR system				Euro 6-2 monitors fuel system under "other ECs systems"	
PCV system				CARB and KOBD monitor for PCV disconnect	
Cooling system				CARB and KOBD monitor for ECT circuit continuity, out of range and rationality; EOBD only for ECT sensor continuity	
Cold start strategies				Malfunctions that only occur during cold start may not be detected by Euro 6-2	
VVT				Euro 6-2 monitors fuel system under "other ECs systems"	Hardware changes are required for variable-lift systems but not for variable-timing
Comprehensive component monitoring				CARB and KOBD require diagnosis of a component if any failure mode causes a measurable increase in emissions for any "in-use" driving, or if failure would impact any other required monitor (e.g., cause disablement) Euro OBD requires diagnosis if any failure mode increases emissions above the thresholds Examples of items required to be diagnosed by OBD II and not Euro OBD: · Customer operated driving mode inputs ("Sport," "Touring," "Eco," etc.) · Transmission sensors and actuators	
Communication protocols – basic				Similar requirements Euro 6-2 requires very similar information, except for VIN and ECU name.	All three require CAN adoption VIN is critical for I/M programs because it provides significant protections against some of the most elementary fraud (clean screening)
Communication protocols – CAL ID/ CVN				Similar requirements	CAL ID and CVN require coordinating with government to develop the database for I/M, and its distribution and updates
Certification testing				Euro 6-2 requires demonstration testing for misfire, catalyst, O2 sensor, and purge	
PVE – Communications					
PVE – Testing					
PVE – IUMPR data					

	Required by the OBD regulation
	Partially required by the OBD regulation
	Not required by the OBD regulation

7. CONCLUSIONS AND RECOMMENDATIONS FOR CHINA

- California's OBD II program is the most comprehensive program in the world and the basis of the European and Korean programs. This program sets the bar for general OBD requirements, MIL illumination and DTC storage, readiness bits and so on, as well as for monitoring conditions. This program has specific OTLs by emission control system and established clear criteria for malfunctions, monitoring conditions, MIL activation and DTC storage and erasing. The program has the most comprehensive set of demonstration testing, before commercializing the vehicles, and product verification testing following vehicle commercialization.
- The Korean program is second in complexity and level of detail. It covers most of the monitoring requirements of the CARB program, leaving out only the product verification sections. One downside of the current KOBD program is that it adopted the European OBD requirements for diesel passenger vehicles, as opposed to the CARB OBD requirements for diesels. This follows the fact that the diesel vehicles in Korea are certified to European standards.
- The first shortcoming of the Korean OBD program is that diesel vehicles have much simpler requirements than gasoline vehicles. The emission thresholds are much more lenient, close to Euro 6-1 values.
- The second important shortcoming of the Korean OBD program is related to PVE testing for communication protocols. In order to have a successful I/M program there needs to be reliable, standardized communication between the vehicle and the test device, and the only way to ensure that occurs is through PVE communication testing.
- The European program is the most simple of the three programs. It leaves many of the emission control systems requirements under "other emission control systems," instead of specifying them, as is the case for OBD II and KOBD. The European Euro 6 OBD program offers an improved version compared to the current China-5 OBD program but leaves many monitoring requirements open to interpretation.

The ICCT recommends adopting CA OBDII with China 6 emission standards, including the specific requirements for diesel vehicles. The Euro 6 OBD program leaves several emission control systems monitoring requirements open to interpretation by manufacturers and regulators. The Korean program is very similar to the Californian OBD program, resulting in similar level of effort for implementation, but has important shortcomings on diesel OBD requirements. Adopting CA OBDII requirements for China 6 could be phased-in with the new standards, while giving additional time to the implementation of requirements for diesel vehicles. This phase-in time is needed to develop capacity among manufacturers and authorities for developing, adopting and implementing the CA OBD II requirements.

California adopted in September 2015 a set of amendments to its OBD II requirements. Although some of those new requirements are specific to LEV-III emissions standard limits, other provisions relevant to vehicle activity and fuel consumption tracking, as well as access to vehicle data for on-road emission testing with portable systems, could be adopted by China as quickly as possible. The data gathered on vehicle activity and fuel consumption could be used to verify new vehicle fuel consumption information that is used by manufacturers for fuel consumption targets compliance, to improve off-cycle credit assessments, and to better evaluate national CO_2 inventories and fuel consumption. Access to data for emission testing with portable systems is a key component of robust compliance and enforcement programs on air-pollution emission standards.

OBD FOR INSPECTION AND MAINTENANCE PROGRAMS

The ICCT recommends adopting these advanced OBD programs as part of the Inspection and Maintenance (I/M) programs for LDVs. This should include access to diagnostic trouble codes (DTCs), readiness bits, reading calibration ID (CAL ID) and calibration verification numbers (CVN), and the development of a national database for these codes. The ICCT also recommends managing of in-use monitor performance ratios (IUMPR) data by national authorities, through the I/M program, to keep track of OBD system performance in use, identify potential deficiencies, and address them in a timely manner.

8. REFERENCES

California Code of Regulations (CCR) (2013). Section 1968.2 Malfunction and Diagnostic System Requirements—2004 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines. Updated September 2013

Ferris, D. H., Van Gilder, J. F., Wang, W., OBD Presentation for China US/CARB OBD Regulations. May 2015.

International Standards Organization (ISO) (2015). Road vehicles—Communication between vehicle and external equipment for emissions-related diagnostics—Part 5: Emissions-related diagnostic services. August 2015. Available at: http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=66368

Ministry of Environment of Korea (MOE) (2015). Regulations for Test Procedure of Manufactured Motor Vehicles. MOE Notification 2015-6 (2015.1.22)

Society of Automotive Engineers (SAE) (2014). E/E Diagnostics Test Modes. August 2014. Available at: http://standards.sae.org/j1979_201408/

United Nations Economic Commission for Europe (UNECE) (2015). Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements. UN Regulation 83 Annex 11