Answers to questions for EMIS hearing, Brussels, 16 June 2016, Prof. Dr.-Ing. Kai Borgeest

1 From an engineering point of view, what are the main adjustments carried out by the engine controlling software on diesel cars, in order for the engine to function both safely and according to current standards?

A present ECU has about 20000 labels (switches, values and maps) to be adjusted; they belong to a smaller number of functions:

1. engine speed and simple vehicle speed limitation/control (complex vehicle speed control systems such as adaptive cruise control use their own ECUs),
2. adjustment of fuel quantity and injection including rail pressure control,
3. adjustment of boost pressure,
4. adjustment of exhaust gas recirculation (EGR),
5. adjustment of glow control (engine ECU or separate ECU connected to engine ECU),
6. adjustment or valve timing (if variable, engine ECU or separate ECU connected to engine ECU),
7. exhaust gas treatment (engine ECU or separate ECU connected to engine ECU),
8. coordination with electrical drive in a hybrid powertrain,
9. diagnosis
10. immobilizer
11. communication to other ECUs (e. g. automatic gear control, driving stability control, energy management)

All these adjustments are not fixed, but depend on the present operation of the car.

2. Which types of adjustments made by engine controlling software affects NOx emissions the most?

Many of these adjustments have small indirect effects on NOx. In particular 2., 3. 4., and 7. have significant direct effects. In particular 4. needs an extremely fine adjustment, too little EGR will increase NOx emissions, too much EGR will increase PM emissions.

3. Shut-off devices are fundamentally illegal unless they are truly necessary to safeguard the engine, as permitted by Article 5(2) of Regulation 715/2007. Do you believe that switching off or limiting the effectiveness of emission control systems is necessary to protect the engine? If so, under which conditions is the justifiable? How likely are these conditions to happen in normal vehicle use in Europe? Which specific emission control technologies could this exemption relate to (EGR, LNT, SCR, DPF etc.), individually or in combination? What will happen to the engine if the emission control system is not switched off under these conditions?

Most of the nearly 20000 labels can be set in a way that a particular function might be completely disabled. EGR, LNT, SCR and DPF require different protection strategies. In many cases this is necessary for drivability, engine protection or pollution control. So it is not critical that the software bears many switching thresholds, but how they are set in a particular case. Besides explicit defeat devices (e.g. switching off exhaust gas cleaning after the test cycle time) some recently known cases also seem to misuse generally reasonable functions to disable emission control for other reasons than permitted by regulation 715/2007.

For EGR a too high EGR rate can damage the EGR actuator and the EGR intercooler, decreases power, increases fuel consumption and increases PM emission.

For exhaust gas aftertreatment systems based on ceramic carriers, overtemperature causes temporal malfunction (SCR) or in extreme cases destruction (LNT, SCR, DPF). In some cases there are choices of materials with different thermal capabilities, e.g. silicon carbide or cordierite for DPF.

4. In the edition No 20/2016 of the German news magazine "Der SPIEGEL" you were quoted to say that the defeat devices found in an Opel Zafira and Astra "have nothing to do with component or engine protection measures". What could be the reason why these defeat devices have been programmed, although both cars have the latest emission reduction technology (SCR) installed? Why is the dosing of urea often greatly reduced in an SCR system, as it has been seen in the most recent Opel case? Why is a minor ammonia leakage not acceptable at tailpipe, if NOx can thus be better reduced?

I was shown excerpts from the Zafira assembly code discovered by the hacker Felix Domke and measurement plots which have been made with a Zafira for the redactions of the print magazine Spiegel the TV magazine Monitor. This reverse engineering work is actually going on. The C source code and its documentation are not available. Besides other findings in the code four switch-off-functions have been emphasized by Monitor and Spiegel as possible defeat devices:

1. EGR reduction at ambient air pressure < 915 mbar (high altitude),

2. EGR reduction and SCR reduction at ambient temperature < 17 °C or ambient temperature > 33 C (“temperature window”),
3. EGR reduction on acceleration,
4. SCR shutoff above 140 km/h or 145 km/h.

Some of them are technically sound, in some cases thresholds are suspiciously close to the conditions of the NEDC which could be a hint to an illegal defeat device. EGR reduces combustion peak temperatures by dilution of fresh air (and the increased heat capacity of the exhaust gas), if the fresh air has already a low density at high altitude, any further dilution of air would cause an overdilution, such an impaired combustion would emit intermediate products (particulate matter, hydrocarbons), so 1. is probably not an illegal defeat device. Concerning the EGR temperature window (2.) see the answer to the next question. Full EGR at acceleration causes a power loss and smoke; to decide if this is a defeat device, it needs to be checked, if the fuel limits are not too close to the engine speed/fuel trajectories reached in the test cycle. I cannot see a reason to switch the SCR at the same temperatures. I cannot see a reason to shut off SCR (4.) at 140 km/h or 145 km/h to avoid overtemperature instead of using the temperature sensor for this purpose. Opel claims to reduce urea to avoid an ammonia leakage, another reason could be the resulting reduction of urea consumption. If the SCR is really leaking ammonia it operates beyond its present NOx conversion limit and a reduction of urea to the quantity which can still convert NOx is reasonable. A small ammonia leakage causes a pungent smell; in high quantity it would be toxic. A countermeasure to ammonia leakage is an additional catalyst which converts the ammonia to nitrogen and water (and to a small extent back to NOx).

5. The Member States’ authorities inquiries (UK, DE, FR) report high discrepancies of vehicle performance in on-road tests compared to the legal NOx limit values. The reports attribute the emission increases on most vehicles to two factors: ambient temperature (the so-called thermal window) and hot restarts. Is there a technically sound reason for switching off the EGR NOx abatement at ambient temperatures such as 17 °C, 10 °C or 5 °C? Are there engineering justifications for always reducing EGR flow rates at temperatures above 0–5 °C and for higher NOx emissions after a hot restart? Would you agree with the UK report assessment that “NOx emissions are generated by high peak temperatures and pressures during the engine's combustion process. A fully warm engine might therefore be expected to generate higher NOx emissions during an NEDC test than an engine which has started from 25 °C”?

An EGR temperature window is reasonable, in particular EGR operation at low temperatures might help to reduce NOx reductions, but would increase other emissions (particulate matter, hydrocarbons) and would cause a premature clogging of the EGR actuator or the EGR cooler. It is suspicious to put the EGR limit with 17°C close to the cycle temperatures above 20 °C. The exact smoke limit of a certain engine typed is not a physical constant, but it must be tried on a test stand or approximately by simulation. NOx emissions increase with combustion peak temperatures. The engine temperature contributes to some extent to the combustion peak temperature.

6. Manufacturers' claim that EGR (Exhaust Gas Recirculation) systems may suffer from intercooler clogging (deposition of "lacquer") at low inlet air temperatures, which is said to increase vehicle maintenance. Temperatures in Europe may vary over a broad range between -25 to 40 degrees and more. Is it possible to calibrate EGR technology to cope with low ambient temperatures? Is this technically difficult and costly to do? Is it technically possible to build cars with engines and emission control systems that work properly under the whole range of ambient temperatures in Europe?

The problem cannot be solved by mere calibration, but there are technical measures available. These measures increase material and/or development costs (e. g. EGR cooler bypass, low pressure or combined low/high pressure EGR, clogging resistant materials, more accurate control models with lower safety margins, more accurate sensors, additional EGR flow sensors, internal EGR). Internal EGR would be most effective, but also by far most expensive, because it requires a variable valvetrain.

7. Emission control systems are active systems, AECC told this committee, adapting themselves to the ambient temperatures, analysing the speeds at certain times etc. In some circumstances software is necessary to protect the engine, in others this was not justified. In general though, the emission tests are predictable and can be manipulated. In-service conformity testing using PEMS is unpredictable and would make it impossible for the software to recognise a testing situation. Do you agree with this statement?

As soon as certain conditions of measurements are defined, it is possible to detect these conditions and use them to cheat exhaust gas tests. Furthermore there are several technical features of a test bench which could be also misused for test bench detection in defeat devices. So I agree that unpredictable road tests with a PEMS can hardly be identified by the ECU test as test cycles. **These road cycles must be absolutely surprising**; otherwise as soon as certain conditions such as temperature ranges are defined, these conditions can be recognized by the ECU software to implement illegal defeat devices and the advantage of PEMS measurements on the roads would get lost.

8. Which information does the car manufacturer receive about the electronic control unit (ECU) from automotive suppliers? Does the manufacturer know the source/proprietary code and the programming details of the software? Or is this unknown to the manufacturer and can the input (data) only be adapted according to the engine´s parameters by the manufacturer? Have all major manufacturer outsourced the programming of ECU software to suppliers or do some manufacturers still program their own software? Should policy makers consider to change legislation in order to grant access to ECU software for market surveillance authorities, in order to investigate suspicious practices easier?

There are two development models. The new modular AUTOSAR software architecture enables the car manufacturer to integrate software modules into the ECU completely independently from the supplier, he can develop own code or he can have third companies to develop software functions.

The classical approach which is still common even with AUTOSAR ECUs is to get the whole ECU including hardware and software (but without calibration data) from the supplier. The software consists of a car independent standard software and usually additional functions requested individually by the car manufacturer. The supplier does not disclose the C source code, but delivers detailed software documentation to the car manufacturer which describes the software in any detail. Some critical functions such as the immobilizer are kept secret on a high security level and might have a separate documentation. The car manufacturer sets the labels and adapts the software this way to the car.

A software disclosure to authorities could help if the following issues are properly addressed:

1. Authorities need additional skilled personnel. This staff must not be subject directly or indirectly to directives from lobby organizations.
2. The software must be documented.
3. Fraud-save technical and legal procedures need to be defined to make sure that the software for analysis is really the same one as implemented in the cars.

Due to the large personal effort a complete coverage of all released codes will not be realistic; a deep analysis of random samples will be more effective than the necessarily superficial attempt to monitor all codes.

9. Can you compare the expected mid-term development of NOx, PM, CO and CO2 emission standards in the EU and the US? Please pick a middle class diesel engine broadly sold in the EU and assess the costs of adapting this engine for the US market.

In particular concerning NOx, PM and CO there have been substantial reductions in the recent years. The CO problem of Diesel engines can be considered practically as solved. NOx and PM have been significantly reduced under laboratory conditions, but not in real traffic. Considering PM, CO and also hydrocarbons there are other serious polluters urban environments which have not been regulated to a similar extent yet. In Germany PM emissions from stationary solid fuel firings (wood stoves) exceed emission from road traffic. Significant PM and hydrocarbon contributions emanate from light motorcycles and working machines which range from small handheld leaf blowers up to heavy construction machines. The latter also contribute to NOx.

A prognosis on future legislation is difficult, due the named facts I guess that in mid-term a strict enforcement of existing limits in real traffic and new limits for light motorcycles, engine driven machinery and stationary urban pollutants will have priority.

It is getting more and more expensive to achieve even minor emission reductions in Diesel engines, on long term Diesel engines for passenger cars will be substituted by hybrid power-trains or even electrical vehicles. Fuel-efficient gasoline direct injection engines will also take a part from the Diesel share, but direct injection gasoline engines emit more NOx and PM than classical homogenous gasoline engines. In the U.S. where limits are stricter already now, the Diesel engine has never found a broad acceptance and the recently increasing acceptance col-lapsed due to recent practices of a car manufacturer, Diesel engines for passenger cars will probably phase out completely in near future there.

For future scenarios also new combustion methods with engine properties between Diesel en-gines and classical gasoline engines come into consideration.

Abbreviations

CO: Carbon Monoxide

DPF: Diesel Particulate Filter

ECU: Electronic Control Unit

EGR: Exhaust Gas Recirculation

NEDC: New European Driving Cycle (remark: this is the old cycle from the nineties to be substituted soon)

NOx: NO + NO_2. Other compounds of nitrogen and oxygen occur in minor quantities only.

LNT: Lean NOx Trap (=Storage Catalyst)

PEMS: Portable Emission Measurement System

PM: Particulate Matter/Mass

SCR: Selective Catalytic Reduction