Screening of emulator devices and potential control methods to detect NOx manipulation

Investigation of NOx manipulation in heavy-duty vehicles
Title:
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1. Background and purpose

Roadside inspections in countries such as Denmark, Norway, Switzerland and Germany have shown that driving with illegal and active emulator devices is a fairly common occurrence, especially among Eastern European truck drivers operating in our area. The Danish authorities, including the Danish police, now need to identify workable roadside inspection control methods to quickly and safely ascertain if a truck has been manipulated.

The truck manufacturers have developed and designed new, modern trucks to meet applicable requirements for exhaust emissions. The requirements are laid down in the so-called Euro norms, where Euro VI is the latest and, so far, the most stringent applicable norm level. In order to adhere to the emissions values in the most stringent Euro norms, trucks must be equipped with advanced emission control systems consisting of the following main components: A particulate filter, a NOx catalytic converter, engine control unit and a tank for AdBlue fluid.

The trucks are designed so that a failure in the emission control system will cause the vehicle to switch to limp mode, limiting engine performance and reducing the attainable driving speed.

To avoid the costs of adding AdBlue, the costs of maintaining the emission control system and the vehicle switching to limp mode, a large market has emerged for the so-called AdBlue emulators, often fitted in a hidden place on the vehicle, which override the vehicle’s engine emission control. The AdBlue emulator sends false, manipulated signals to the vehicle’s engine control unit confirming that the system is working, which prevents the vehicle from switching to limp mode. The driver may thus continue driving with a disconnected emission control system, resulting in significantly increased emissions of particularly NOx.

For example, an AdBlue manipulated Euro VI vehicle would produce emissions corresponding to the level of a 20-year old Euro I vehicle. The properly functioning AdBlue system removes up to 98% of the NOx produced, but if the truck is manipulated, the NOx-reducing process is completely disabled.

In addition to NOx manipulation, other forms of tampering have been seen, for example, removal of the particulate filter, resulting in significantly increased particulate matter and noise emissions.

This report and the associated studies are carried out with the purpose of establishing which procedures, methods and equipment can effectively detect modified trucks during roadside inspections. The work is carried out by the Danish Technological Institute on behalf of the Danish Road Safety Agency.

The report is structured according to the following four main areas:

- **Screening of emulator devices**, describing the market and function.
- **Potential control methods**, identifies potential operational control methods for detecting NOx manipulation.
- **Neighbour check**, looking at the situation in other countries; Which emulator devices are found and which methods are used to detect NOx manipulation?
- **Pricing**, specifying which costs are expected for operation and maintenance of an engine emission control system.
2. Conclusions and recommendations

2.1. Screening of emulator devices

Emulator devices are all types of electronic devices fitted to the truck’s wiring harness with the purpose of disconnecting the vehicle’s engine emission control. Electronic equipment for NOx manipulation is colloquially called an "AdBlue emulator" or a "NOx emulator". The term "emulator" is derived from the fact that the emulator mimics, or "emulates" the continuous signals normally sent by the truck’s AdBlue system to the vehicle’s engine control unit. The computer requires constant feedback in the form of data from the vehicle’s engine emission control in order to verify that the system is actually working as intended. If data is not received, or if data is not within the value ranges specified, the driver will receive error messages.

In other words, emulator devices are electronic equipment designed to generate and send the required data, which is, however, manipulated (false), to the vehicle’s engine control unit, which is tricked into believing that the system is working as intended, thus allowing disconnection of the engine emission control.

There are different types of emulator devices, which can be divided into the following main groups:

- OBD emulators (a former type of emulator fitted in the vehicle's OBD connector)
- CAN emulators (the current type of emulator fitted to the vehicles wiring harness)
- Passive components (a less refined method. Connected to sensors in the vehicle's wiring harness)
- Modification of the engine control unit (an advanced method that requires specially designed equipment for installation of engineered software in the vehicle’s engine control unit)

The various installation methods and functions are explained in detail in section 3.2

With up to 100 [1] different providers of AdBlue emulators, it is relatively easy to acquire an emulator device. Although Chinese manufacturers top the list of providers, there are also a large number of providers on the European continent, and at prices between DKK 600 and 6000, there is an emulator for every budget. Whereas the cheapest emulators are simple to use and often easy to detect, the more expensive models are often very advanced, programmable devices in sophisticated packaging which leave very few traces. They are difficult to detect visually and as they have intelligent programming, they are also difficult or outright impossible to detect with standard OBD error code readers. Error code readers are special hand-held computers which garages or the police may use to read out the vehicle's error code directory. Emulator devices thus constitute a significant challenge for the control authorities, because it takes extensive knowledge, availability of workable control methods and measuring equipment to detect them.

The Danish Technological Institute’s experience and measurements performed on a purpose-bought emulator device for a Euro VI truck demonstrates that the device works as intended and can even be remote-controlled from the steering wheel. Our measurements show that disconnecting the engine emission control results in drastically increased NOx emissions; they increase by a factor of 50. Removing the particulate filter, which is recommended by the emulator provider, will also lead to drastically increased particulate matter emissions.
emissions. The particulate filter generally removes 98% of particulate matter. If the particulate filter is removed, the exhaust will be discharged to the atmosphere in its raw and untreated form.

2.2. Potential control methods

Detection of NOx manipulation is a difficult discipline, because the developers put a lot of effort into the design and installation of AdBlue emulators. The first AdBlue emulators were simple both in terms of installation and functionality, but the developers of AdBlue emulators have now become very experienced both in relation to sophisticated design of emulator functionality and of emulators that leave very few installation traces. Emulators are becoming physically smaller and in combination with professional installation, they are becoming very difficult to detect in a visual inspection.

The most probable approach moving forwards is to use several control methods which when combined ensure that all manipulation is detected. A common trait when using AdBlue emulators is significantly increased NOx emissions from the vehicle, regardless of the type of emulator used. Therefore, one of the best methods to detect manipulation is to perform an emissions measurement on the vehicle. Implementing an operational procedure accompanied by portable measuring equipment is assessed to be the method which will detect the vast majority of manipulated vehicles. Disconnecting the emulator during a roadside inspection is an obvious trick that will allow the truck driver to slip through the inspection. Therefore, emissions measurements should be supported by supplementary control methods where the obvious choice is visual inspection combined with readout of system status using an OBD error code reader.

Our investigation of a NOx emulator tested on a vehicle, which is described in section 3.5 of this report, indicates that emissions measurement during acceleration should be considered as a control method, because it only takes three to four accelerations to ascertain if the engine emission control is actually working or has been manipulated. It only takes a few minutes per vehicle to perform acceleration measurement, which is assumed to be acceptable for roadside measurement. There are a lot of mobile devices available at prices of around DKK 30-50,000. When choosing the device, response times should be considered to ensure that the device is “fast enough” to detect and report emissions values during acceleration.

Remote sensing is a measuring method which does not measure directly on the exhaust pipe of the vehicle. The equipment is placed on the roadside, continuously measuring emissions as vehicles pass the measuring point. With remote sensing, it is possible to check a large number of vehicles within a very short time. However, the measured data must be analysed and the vehicle Euro classification must be identified before a decision to pull over and check the vehicle due to increased emissions values is made. Roadside remote sensing where remote sensing equipment is placed in the control authority’s vehicle, as has been tested in Germany, is assessed to be an interesting control method, because the truck will be operating during the measurement, and as the driver will normally not be aware that his vehicle is being checked, the AdBlue emulator will most likely be connected if such device is installed. The challenge of this measuring method is that it is still at the developmental stage and that fully developed equipment is not available on the market. The method is assessed to be relevant for emissions screening of traffic at selected checkpoints.

Remote sensing may also be used for assessment of road traffic emissions in air quality...
studies and presumably for screening vehicles with very elevated nitrogen oxide (NOx) and possibly particulate matter emissions and selecting vehicles for further testing.

<table>
<thead>
<tr>
<th>Method</th>
<th>Brand-specific</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>No¹</td>
<td>The method should be used and refined as it is done now with experiences from already detected manipulations. A challenge is that this detection procedure will always be one step behind the developers, which means that the latest emulator models will be able to slip through an inspection because they may be hidden in the vehicle’s wiring harness. In addition, the purely digital manipulations, e.g. software reprogramming of a chip in the engine control unit, will not be detectable, as such manipulation would leave no installation traces. However, it requires specialised equipment and knowledge to perform digital manipulation, and it is still unknown how widespread this method will become.</td>
</tr>
<tr>
<td>OBD/CAN bus</td>
<td>Yes²</td>
<td>The method should still be used as a support tool, specifically for the visual inspection. The method could be improved if instructions for use of specific equipment for specific vehicles are prepared, like those prepared for visual inspection.</td>
</tr>
<tr>
<td>Emissions measurement</td>
<td>No³</td>
<td>An obvious method, which will be able to detect most NOx manipulated vehicles during roadside inspections. Preparation of operational procedures and identification of suitable portable emission measuring equipment remains to be completed. The operational procedures must include establishing the vehicles’ operating mode during measurement, establishing load and any measurement distances necessary. Portable equipment for emission measurement must be identified with particular emphasis on sufficiently short response times.</td>
</tr>
<tr>
<td>Remote sensing</td>
<td>No³</td>
<td>The method is still being developed. The method is assessed to be relevant for emissions screening of traffic at selected checkpoints. Furthermore, the method will become interesting if portable equipment to be used in the control authority’s vehicles becomes available.</td>
</tr>
</tbody>
</table>

1. The location of emulators is often brand-specific, which is why knowledge of the current locations on different vehicles will be an advantage.
2. Brand-specific or after-market error code reader.
3. Knowledge of the measured vehicle’s Euro class is required in order to be able to determine the allowable emissions.

**Figure: 1 Summary and conclusions on potential control methods.**
2.3. Neighbour check

As expected, the neighbour check shows that NOx manipulation is a major problem in Europe. In general, there is no specific formal cooperation across national borders. Some countries have already implemented routine inspections, e.g. Switzerland, where a large number of vehicles are checked daily at the HTCCs (Heavy Traffic Control Centres).

Some countries, e.g. Norway, England and Switzerland have prepared or are preparing procedures to detect NOx manipulation, just like the Danish police has a comprehensive guideline for brand-specific inspection of vehicles in connection with roadside inspections.

ACEA, the European Automobile Manufacturers’ Association, has implemented a number of initiatives, investigating the AdBlue emulator market\[^1\] and, not least, the emulators’ functionality\[^2\] in different trucks. There are no specifically developed control methods for vehicle inspection under ACEA.

Our neighbour check shows that in Switzerland, the Uri canton police has prepared a comprehensive guideline based on visual inspection, which is used during routine checks at the traffic control centres.

Based on reports from the neighbour check, the conclusion is that there is a need for pan-European coordination and development of control methods, taking the current visual inspections to the next stage and supplementing them with workable measuring methods. Our investigation shows that use of OBD error code readers and advanced CAN bus analyses as well as procedures for emission measurements are potentially strong tools to reinforce the efforts to fight NOx manipulation at European level.

2.4. Pricing

Saving the cost of AdBlue is generally emphasised as being the main motive for NOx manipulation. The potential cost savings on AdBlue of course depends on mileage and this is supported by the general numbers from our sources [33], which show savings of up to DKK 15,000/year at an annual mileage of approx. 150,000km. A study of the total operating costs for an emission control system, i.e. the costs of both AdBlue and service and maintenance, shows that the cost of service and maintenance constitute a significant amount. In general, it is found that an emission control system has a long service life [34], presumably prompted by EU approval requirements, which require a service life of at least 700,000 km. Therefore, comprehensive repairs will not be required for the first approx. one million kilometres, after which the repairs are costly as they will often comprise replacement of SCR catalytic converter and possibly more or less vital parts of the control or auxiliary equipment.

Manipulating the engine emission control is thus a very cheap alternative to replacing the SCR catalytic converter, which gives reasonable grounds to suspect that it is the desire to postpone or completely avoid expensive repairs that is the reason for installing an AdBlue emulator as much as it is to avoid the AdBlue costs. It is reasonable to assume that many of the manipulated vehicles have defective systems, which means that the vehicles are kept in operation only by means of an AdBlue emulator.
3. Screening of emulator devices

The emulator devices often consist of an electronic device called an **AdBlue emulator**, which is installed in a hidden place and connected to the vehicle’s wiring harness. The purpose of the AdBlue emulator is via electronic signals to disable the vehicle’s OEM AdBlue system.

AdBlue is a chemical fluid; more specifically, it is a urea solution at 32.5% in demineralised water required for the vehicle's SCR catalytic converter to work and transform the environmentally harmful NOx into harmless water and nitrogen. Without AdBlue fluid, the SCR system does not work, resulting in a drastic increase of the vehicle’s NOx emissions.

![Illustration: Teknologisk Institut](image)

**Figure 2: Overview of affected vehicle components**

In addition to disabling the vehicle's original AdBlue system, the AdBlue emulator blocks a number of error codes and error messages that would otherwise be triggered when the vehicle’s electronics are tampered with. If error messages in the truck's dashboard are ignored, the vehicle will, after a short period of time, switch to the so-called limp mode, reducing the vehicle’s performance. The vehicle manufacturers build in this functionality to force the driver to service the vehicle if the engine emission control does not work properly.

Blocking error codes and error messages comprises:

- Disabling the vehicle’s main diagnostics light (“the yellow engine light”).
- Disabling the AdBlue system indicator lights.
- Manipulating the AdBlue tank gauge.
Investigation of NOx manipulation in heavy-duty vehicles

- Switching off the "limp mode", which reduces engine power when driving without AdBlue.
- Potentially blocking for readout of error codes related to the engine emission control via the OBD error code reader.

AdBlue emulators are used for two specific reasons:

1. Saving the cost of AdBlue fluid.
2. Avoiding expensive repairs of faulty components in the vehicle's engine emission control.

Generally speaking, AdBlue emulators are available for all new trucks as well as for tractors and construction machinery. AdBlue emulators are brand-specific and tailored to individual vehicle brands.

With a properly functioning AdBlue emulator, the driver has full engine power and he may not notice if the vehicle has an AdBlue emulator installed, because pull is completely unchanged, and error messages do not occur on the truck’s dashboard.

### 3.1. Supply of emulator devices

It only takes a few seconds to find a supplier of AdBlue emulators on the internet. Using the keyword "AdBlue emulator" on Google returns a very large number of search results with addresses of providers.

An even more obvious choice is probably to buy an AdBlue emulator from one of the known e-commerce sites that all offer the product with the keyword “AdBlue emulator”.

<table>
<thead>
<tr>
<th>e-site</th>
<th>eBay</th>
<th>Amazon</th>
<th>Allegro</th>
<th>Alibaba</th>
<th>MadeinChina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hits</td>
<td>155</td>
<td>3</td>
<td>183</td>
<td>639</td>
<td>133</td>
</tr>
</tbody>
</table>

*Figure 3: Number of hits on "AdBlue emulator" on the most well-known e-commerce sites.*

The company [http://bildiagnose.dk/biltester/item/adblue-emulator](http://bildiagnose.dk/biltester/item/adblue-emulator) is one of the few sites advertising AdBlue emulators in Danish.

When searching for "chiptuning," there is a large number of hits for Danish providers that offer this service. This service is primarily aimed at passenger cars, but when searching for "chiptuning af lastbiler" (chip tuning of trucks), five Danish companies pop up offering this service, however, not only for trucks, also for tractors and construction machinery.

The following Danish companies offer modifications of engine control units for trucks:

- [http://www.sancodk.dk/](http://www.sancodk.dk/)
- [http://www.rh-motorsport.dk/lastbil.html](http://www.rh-motorsport.dk/lastbil.html)
- [http://www.motor-optimering.dk/](http://www.motor-optimering.dk/)
- [http://stage3.dk/traktorlastbil-tuning/](http://stage3.dk/traktorlastbil-tuning/)
- [http://www.lastbiltuning.dk/](http://www.lastbiltuning.dk/)

Modifying the engine control unit via the vehicle’s diagnostic connector, embedding a modified engine control software in the vehicle’s engine control unit. The websites claim that this type of tuning will achieve improved engine performance and better mileage. However,
it is unclear how this chip tuning or engine control unit modification impacts emissions. With a promised performance increase of up to 35%, it must be assumed that emissions will deviate significantly from type approved values, just as it cannot be ruled out that outright manipulation of the engine emission control will be carried out at the same time.

An example of equipment for reprogramming of the chip in the vehicle’s central engine control unit can be seen at [http://www.flashtec.ch/](http://www.flashtec.ch/). Flashtec SA is a Swiss company providing equipment and software for various types of tuning of passenger cars, trucks, construction machinery and tractors. The equipment must be classified as specialist equipment that is not readily operable without fairly in-depth knowledge of engine control units and their data structure. The price of the equipment is also considerable, as the price of a complete set of equipment for reprogramming is around DKK 150,000. Even though the company offers complete software packages tailored to the customer’s wishes, comprehensive knowledge is still required to install the software packages in the vehicle. At the same time, the programmer must have access to the vehicle in order to install the new software.

In a previous study performed by Statens Vegvesen in Norway [3], 21 different types/categories of AdBlue emulators were identified. Prices start at a few hundred kroner for a basic Chinese emulator, while a high-end European emulator costs around DKK 5,000. Emulators for new Euro VI-compliant trucks are significantly more expensive than emulators for older models.

ACEA has worked with NOx manipulation, including the supply of AdBlue emulators from different geographic markets. In 2017, ACEA identified 87 unique providers. The geographical spread of the results is illustrated below.

![GEOGRAPHICAL SPREAD](https://example.com/geo.png)

* AU, BU, CZ, EE, IE, IT, LV, PT

** Brazil, Russia, Singapore, Turkey, Ukraine

**Figure 4: Geographical spread of 87 unique providers of AdBlue emulators [1]**

We purchased a high-end emulator for the latest Scania Euro VI-compliant vehicles from a Polish website, [https://trucktool.pl](https://trucktool.pl). The emulator was of the Sercon make, and the price
was approx. DKK 5,000 including shipping. The emulator was delivered to our address two days later.

The emulator could be programmed to automatically become inactive below a defined speed, e.g. 4km/h. The AdBlue system thus works as intended when the vehicle is idling. This prevents the emulator from being detected during emission measurements at a roadside inspection, where the vehicle is idling. However, we have not tested this functionality because the required software to reprogram the Sercon emulator to have this functionality was not available to us.

A comprehensive installation video is available on the website. The video, among other things, shows how the driver can connect and disconnect the emulator via the dashboard. This was the configuration tested and reported.

![Figure 5: Image from instruction video showing available software for setting up the Sercon AdBlue emulator. Please note that you can select the control method; either steering wheel or automatic disconnection at a given speed. Furthermore, it is possible to specify the level of the AdBlue tank. In our case, the AdBlue tank level indicator was set to 68%. Finally, the LED light on the emulator can be switched off, making it even harder to locate in a visual inspection.](image)

### 3.2. Types of emulator devices

Common to all emulators is that they are all electronic devices, which must be connected to the vehicle's engine control unit, the so-called CAN bus (Controller Area Network) in order to work. The electronic devices disconnect the AdBlue system in such a way that the vehicle’s dashboard warning lights and the vehicle’s limp mode, limiting engine performance, are disabled.
Over the years, we have seen various types of AdBlue emulators. The older types of AdBlue emulators could be connected directly through the vehicle's diagnostics connector, which is very simple, but this type is now seen less often because it is inherently very easy for the control authority to locate it. Most systems today are installed through actual intervention in the vehicle’s wiring. In other words, it is a job for specialists and not something a driver will normally be able to do. In future, the procedure will most likely be a pure software-related intervention, changing the engine control unit and leaving no physical traces. Emulators can be divided into four main areas:

1. Simple installation in the diagnostics connector, called OBD installation.
2. Installation in the vehicle’s wiring harness called CAN installation (Controller Area Network).
3. Passive components placed in the wiring harness.
4. Reprogramming of the vehicle’s engine control unit, entailing software modification or chip replacement.

<table>
<thead>
<tr>
<th>OBD installation (early model)</th>
<th>CAN installation (current model)</th>
<th>Passive components (less used)</th>
<th>Reprogramming of engine control unit (newest method)</th>
</tr>
</thead>
</table>

**Figure 6: The four main types of emulator boxes**

The immediate advantage for the truck driver of the **OBD installed** device is that it is very easy and quick to install, but on the other hand it is also easy and quick to detect for the control authority. In terms of price, these emulators are in the low price range, and they are usually less sophisticated as the OBD connector does not necessarily give access to the entire CAN. This means that the possibility of including the more advanced features is limited.

The main characteristics of the **CAN-installed** devices are that they are installed directly in the vehicle’s central CAN where the smart devices, receive and send commands to the vehicle’s engine management system. Direct installation in the vehicle's CAN enables access to all of the vehicle’s CAN signals, which means that it is basically only the programmer’s skills, insight and ingenuity that sets the limit for how intelligent the design of the emulator can be. The more sophisticated and programmable devices of the CAN-installed type feature connection and disconnection at a set speed or steering wheel remote control. However, installing the device in the vehicle's CAN always leaves traces, even though the smallest ones may be difficult to locate. Whereas the OBD-installed type by its very nature can always be found in the OBD connector in the vehicle’s cab, CAN-installed emulators can be fitted anywhere in the vehicle’s CAN bus. This means that they can be extremely
well hidden in the vehicle's wiring harness, often in inaccessible places such as on the vehicle's chassis or in concealed spaces in the cab.

A less sophisticated but still applied method of NOx manipulation is the incorporation of passive components in the wiring. The passive components are not installed in the CAN bus, but are often installed in connection with e.g. temperature sensors. The passive components make use of the fact that most vehicles disconnect the AdBlue system if the outside temperature is below a specific value. With passive components, the vehicle may thus be led to believe that the outside temperature is always below the limit, at which the pre-installed system would always disconnect the AdBlue system anyway. It is so to speak the vehicle itself which disconnects the AdBlue system in order to be able to continue operating without alarms, error messages or switching to limp mode. Unlike the more intelligent emulators, passive components are not programmable, which means that the driver cannot reconnect the AdBlue system during e.g. a roadside inspection, which means that such passive components may be found during an inspection or when emissions measurement is performed on the vehicle.

The latest and most sophisticated AdBlue emulator type is the so-called modification of engine control unit. In this case, the emulator is built into the vehicle's engine control unit purely in the form of a software package. Alternatively, one or more engine control unit computer chips are replaced with versions containing the software for manipulation of the vehicle. Software containing manipulation algorithms is also installed, either by reprogramming the vehicle's OEM chip or by replacing the OEM chip (or circuit board) with an after-market chip containing the manipulation software. Modifying the engine control unit only leaves digital traces which are very difficult to locate and document. Replacing one or more chips usually leaves traces when opening the electronics or when soldering the circuit board. It remains to be seen how prevalent this kind of manipulation will become. Using manipulated engine control units requires fairly advanced equipment in order to be able to communicate with the engine control unit, and it also requires relatively extensive knowledge to perform the necessary reprogramming of the massive and advanced data structure of the engine control unit software.

3.3. Installing emulator devices

The vehicle data network is called CAN (Controller Area Network). Control units in a CAN are connected as a network, colloquially the CAN bus, which means that all signals pass through all control units. Each control unit is responsible for sorting incoming signals. Each control unit can both receive and send signals in the network. In other words, commands to other control devices can be sent from anywhere in the CAN bus. A vehicle is equipped with a series of CAN controllers, each of which has a specific function, such as window operating controls, windscreen wipers, audio system, air conditioning, ABS, airbags and the more advanced controllers such as for the engine control unit (ECU) or the engine emission control.
Figure 7: Schematic representation of a CAN bus where vehicle communication goes through two wires.

As shown in Figure 7 above, CAN bus communication takes place in just two wires, which are called CAN high and CAN low, respectively. It thus only takes two wires to connect to the CAN bus. The two wires are either fixed by means of soldering, a set of alligator clips or just scotch-lock wire connectors as shown in Figure 8. In addition to the absolutely essential CAN-bus connection, most AdBlue emulators need more wires to be connected. This is usually two wires which get power supply from the vehicle’s battery and there may be one or more additional connections, usually control signals, which can be used for functional or control purposes. This could for example be for remote control of the emulator, by means of a remote control, a hidden switch or from the menus on the vehicle’s steering wheel.
Figure 8: Access to the CAN bus is achieved through installation of a simple scotch-lock wire connector, which is snapped over the two CAN bus communication wires; CAN high and CAN low.

CAN bus commands are not encrypted, so with the right knowledge and the right equipment they are fairly easy to read. Reading the commands and sending functional commands via the CAN bus does, however, require some knowledge of the data structure which is designed by the manufacturer. It is possible that this information is partly decoded from the OBD repair and maintenance information, which the manufacturer is obligated to provide in accordance with the regulation of the European Parliament, and partly that the data structure has been disclosed by means of hacking. There is a large selection of CAN readers and other tools for CAN hacking available on the market. An efficient and comprehensive piece of literature, which we have also purchased, is shown in Figure 9.

Figure 9: Example of comprehensive technical literature providing guidance on CAN hacking

The installation of the AdBlue emulator will depend on the type of emulator chosen. Whereas the OBD-installed type is just connected to the vehicle’s OBD connector, the CAN-installed type is a bit more complicated as you need to be able to locate the right CAN and wires. However, this is usually done by the manufacturer of the AdBlue emulator, because the emulator is often accompanied by a more or less detailed installation manual for the specific vehicle. For an example of an installation manual, please go to https://trucktool.pl
Figure 10: An AdBlue emulator can be installed in three ways. 1.) Installation of OBD type emulator directly in the OBD connector – a method used earlier. 2.) CAN installation, which is the most common type of installation where the emulator is installed in the CAN wiring between the EEC (Engine Emission Control) and the ECU (Engine Control Unit). 3.) Modification of engine management system, which may be the method of the future. Performed by reprogramming the electronics in the engine emission control or in the engine control unit (ECU). 4.) Passive components that are installed in connection with temperature, level or NOx sensors.

Which physical installation method to use depends on what is practicable and also on which method leaves the fewest installation traces. For the Polish Sercon emulator purchased by Danish Technological Institute for the project, the installation manual prescribed installation in one of the central connectors on the vehicle’s chassis. An immediately visible location, but the emulator was provided with wires of exactly the same colour as the vehicle’s wiring. With the emulator came something that resembled OEM connectors and rubber grommets, which could be used for installation. It was thus possible to do a very professional installation leaving only few installation traces. The only challenge was to hide the emulator on the chassis.
3.4. Functionality

When fuel is combusted in an engine, soot particles and nitrogen oxides etc. are produced. Due to their harmful effects on human health and the environment, in modern vehicles exhaust gases are cleaned in two main phases; in the particulate filter (only Euro VI) and in the NOx catalytic converter.

The particulate filter, which functions as a physical filter, removes around 95-98% of soot particles. Filtering does not require addition of reactants, but the filter should be cleaned at appropriate intervals in order to avoid clogging. Cleaning takes place automatically, as soot particles are burnt when the engine is running at appropriately high speeds, e.g. while driving on the motorway. If this is not sufficient, it is possible to inject fuel into the particulate filter, thereby initiating the combustion of soot particles. The process is controlled continuously by the engine emission control (EEC), which constantly monitors the functioning of the filter and starts the cleaning process when back pressure reaches a certain level. A very central problem when installing an AdBlue emulator is that this monitoring and regeneration of the particulate filter is disabled. To solve this, most suppliers of AdBlue emulators recommend that the particulate filter be removed. Removing the particulate filter means that particulate emissions increase significantly and often to a level equivalent to a 20-year-old Euro I-compliant vehicle. At the same time, removing the particulate filter may increase noise emissions from the truck because of the particulate filter’s noise reducing effect.
The NOx catalytic converter works differently. Sensors continuously measure exhaust temperature and NOx level before and after the catalytic converter. Based on the sensor readings, the engine emission control calculates and controls the injection of AdBlue, which as a reactant ensures that harmful NOx (NO and NO2) is converted into harmless water and nitrogen by means of a catalytic process called selective catalytic reduction (SCR). Depending on the vehicle’s load point and the system design, between 70 and 98% of nitrogen oxides are removed in this way. When installing an AdBlue emulator, the emulator takes over control of the engine emission control and deactivates the injection of AdBlue.

![Figure 12: Illustration of components that are usually disconnected when installing an AdBlue emulator. The AdBlue emulator takes over control of the engine emission control, which is in practice disabled. Generally, the particulate filter may be removed as well, which means that the engine exhaust gas is discharged untreated to the atmosphere.](image)

When the AdBlue emulator takes over control of the engine emission control, its main function is to disconnect the AdBlue injection. Normally, such disconnection would result in the vehicle’s warning lights going on to warn the driver that the engine emission control must be serviced. If this is neglected, the vehicle will within a short period of time switch to limp mode, which means that engine performance is reduced and ultimately that the vehicle will not start. Therefore, the AdBlue emulator is programmed to continuously send false signals, also called emulated signals, to the vehicle’s engine control unit reporting that “all is clear”. It means that warning lights do not go on and that the driver can continue driving without any indication that the vehicle’s AdBlue system has been disconnected.

There is no recipe or standard defining which signals are to be sent to the vehicle’s key engine control unit in order for it not to report an error. The data architecture is brand-
specific to each truck manufacturer and may even be specific for each model of a brand. This explains why there is no "one size fits all" emulator, and that an emulator must actually be built and programmed for each specific type of vehicle.

In 2016 and 2017, ACEA (European Automobile Manufacturers’ Association) performed a study of five Euro V and six Euro VI emulators at prices between EUR 30 and EUR 800. The study looked into which signals are typically manipulated, and they were: AdBlue tank level, back pressure over the particulate filter and exhaust temperatures in different stages of the aftertreatment system.

The figure above shows an example of how an emulator generates false signals about particulate filter back pressure. The false signals are based on the percentage engine load. The emulator is as such capable of reading the CAN bus code containing information about engine load. Based on this information, the emulator generates a false signal for particulate filter back pressure which is sent to the vehicle's engine control unit. As the signals are within the expected values, not error is reported. This kind of manipulation also allows for removal of the particulate filter without the vehicle engine control unit reporting an error.
Figure 14: The emulator sends false signals about aftertreatment system temperature \[^2\].

The figure shows an example of how an emulator generates almost perfect, yet false, signals about the temperature in the aftertreatment system. Thereby tricking the vehicle’s engine control unit into thinking that everything is fine so no error codes are triggered.

3.5. **Documentation of an AdBlue emulator’s effects on a vehicle**

To document the effects of an AdBlue emulator on an actual vehicle, Danish Technological Institute purchased a Polish AdBlue emulator and installed it in a Euro VI-compliant truck.

The AdBlue emulator, which was brand and model specific, was purchased on a Polish website, [https://trucktool.pl](https://trucktool.pl), was delivered within a few days and included an installation manual. The AdBlue emulator was installed in the vehicle according to the manufacturer’s instructions, and the vehicle was tested on a chassis dyno with the emulator connected and disconnected. During testing, detailed emission measurements were performed in different operating scenarios to document the effect on specifically NOx emissions in order to recommend potential control methods.

<table>
<thead>
<tr>
<th>Make</th>
<th>Scania R410</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro classification</td>
<td>VI</td>
</tr>
<tr>
<td>Engine performance</td>
<td>410/300 HP/kW</td>
</tr>
<tr>
<td>Year</td>
<td>2014</td>
</tr>
<tr>
<td>Odometer</td>
<td>480,000km.</td>
</tr>
</tbody>
</table>

*Figure 15: Test truck specifications*
Figure 16: Truck placed on chassis dyno at Danish Technological Institute’s garage in Aarhus. In the photo, the vehicle is ready for testing. The white box behind the cab is the portable emissions measurement system (PEMS).

The measurements were made at Danish Technological Institute’s engine laboratory in Aarhus where the truck was tested under load on a truck chassis dyno. During testing, continuous measurements of correlated load and emission values were performed.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Measuring parameters</th>
<th>Measuring range</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHS chassis dyno</td>
<td>Impact on wheels</td>
<td>0-500kW</td>
</tr>
<tr>
<td>AVL GasPEMS iS</td>
<td>O₂</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>5000ppm</td>
</tr>
<tr>
<td></td>
<td>NO₂</td>
<td>2500ppm</td>
</tr>
<tr>
<td></td>
<td>Exhaust flow</td>
<td>6-410HP</td>
</tr>
<tr>
<td></td>
<td>Exhaust temperature</td>
<td>0-600°C</td>
</tr>
<tr>
<td>FTIR Antaris IGS</td>
<td>NH₃</td>
<td>1-1000ppm</td>
</tr>
</tbody>
</table>

Figure 17: Measuring equipment used to test the truck
The tested operating scenarios are described in the table below:

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Load scenario</th>
<th>Duration [min.]</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cold start</td>
<td>30</td>
<td>Measuring basic emissions for cold start and start of a conditioned engine and NOx catalytic converter</td>
</tr>
<tr>
<td></td>
<td>Constant load 45kW</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Constant load 90kW</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Constant load 180kW</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Idle after constant load</td>
<td>Approx. 30</td>
<td>Assessing the vehicle’s emissions level without load, for example during a roadside inspection</td>
</tr>
<tr>
<td>3</td>
<td>High idle at 1500rpm with cold NOx catalytic converter</td>
<td>5</td>
<td>Assessing whether high idle can be used as a control method for roadside inspections</td>
</tr>
<tr>
<td>4</td>
<td>Acceleration test</td>
<td>4x2</td>
<td>Assessing whether acceleration under load can activate a cold NOx catalytic converter</td>
</tr>
<tr>
<td>5</td>
<td>Measuring ammonia slip (Only relevant when emulator is disconnected)</td>
<td>Measured throughout the test</td>
<td>Assessing if measuring ammonia slip can be used to screen for active and functioning NOx catalytic converter</td>
</tr>
</tbody>
</table>

**Figure 18: Table of the five different operating scenarios, which were tested with the Sercon AdBlue emulator connected and disconnected, respectively.**

The choice of load points for the constant load tests and partly for the idling tests is based on the Swiss TeVeNox model [18], which works with measurements of NOx emissions at different load points as well as measurements of vehicle emissions as a result of SCR system cooling. The three load points selected correspond to 15, 30 and 60% engine load, respectively. The high idle scenario was inspired by the method used for periodic inspections of passenger cars. The acceleration test was inspired by the Danish public transport companies’ environmental inspection programme for buses. Assessment and measurements of ammonia slip are inspired by talks with the police.
Figure 19: Cycle no. 1 without NOx manipulation.

Figure 19 shows the results of the first constant load test of the truck while it was in its standard configuration, i.e. the AdBlue emulator is disconnected. The first phase of the test is to cold start the truck and after 30 minutes of idling, the load test itself starts with incremental load increases. The first load step lasting 30 minutes at 45kW is represented by the orange curve on the diagram. The following load points are 90kW for ten minutes and finally, 180kW for five minutes. The grey curve in the graph shows the exhaust temperature in the exhaust pipe and the blue curve shows the associated NOx emissions. It is evident that the engine emission control is inactive during the entire start-up sequence (idle period), but when applying load on the truck’s wheels, the exhaust temperature rapidly rises. At around 250°C, the NOx catalytic converter starts, resulting in drastically decreasing emissions to a level of approx. 10-20ppm, an impressive low level, which the truck maintains despite the load changes imposed.
Figure 20: Cycle no. 1 with NOx manipulation.

Figure 20 shows the results of a test sequence identical to the one in Figure 19. The only difference being that the AdBlue emulator is connected. Again, we have a test sequence initiated with a cold engine. The time spent on the individual phases is identical to the previous load test shown in Figure 19, and the colours of the curves are identical as well.

The figure clearly shows that the SCR catalytic converter is inactive at all times, and NOx emissions increase as the load increases. At a load of 180kW, which corresponds to approx. 60% engine load, NOx emissions are around 950ppm, which is approx. 45 times higher than when testing the standard configuration.

Load tests show that there is a very big difference in NOx emissions with and without the AdBlue emulator activated. The conclusion must be that emission measurements of vehicles can be considered a potential control method for vehicles under load.
Figure 21 shows the truck idling after the load test. Engine speed, illustrated by the yellow curve, shows that the engine speed is constant at approx. 600rpm, which is the vehicle's standard. If we look at NOx emissions, there is an initial phase of approx. four minutes when the NOx emissions vary chaotically, after which the vehicle gains control over the situation. As long as the temperature is above approx. 250°C in the exhaust pipe, the SCR catalytic converter is active and NOx emissions are at virtually zero for another five minutes, after which the AdBlue system switches off. Please note that throughout the test, the exhaust temperature is constantly falling – the grey curve. When idling, the vehicle is thus not capable of maintaining a high enough temperature in the SCR catalytic converter for it to remain active. Again, the SCR catalytic converter switches off at a temperature of around 250°C.

Emission measurement during idling is thus only an option if the temperature in the SCR catalytic converter is high enough for it to be active. At the same time, the fluctuations in NOx emissions will interfere with emissions measurements. It is, however, unknown if such fluctuations are normal for Euro VI-compliant vehicles or if they only occur on Scania vehicles or even only on this vehicle. The reason for these fluctuations should be investigated further.
Figure 22: Cycle no. 2, again comprising idling after load test. The vehicle is manipulated, i.e. the AdBlue emulator is connected.

Figure 22 shows the idling test repeated, but this time with the AdBlue emulator connected. No change in the SCR catalytic converter function is seen as it is disconnected, but there is a clear difference compared to Figure 21, because the NOx emissions are constantly high and unchanging after approx. ten minutes. There is no immediate explanation for the almost time constant peaks in NOx emissions.
Figure 23: Cycle no. 3 where the vehicle is not manipulated, i.e. the AdBlue emulator is disconnected. High emission levels are seen during high idling.

Figure 23 examines whether high idling and increased engine speed in a vehicle without load can be used as a control method. For this test, the AdBlue emulator is disconnected and the SCR catalytic converter has been cooled to a level where it is not activated. High idle does not appear to have any significant influence on the SCR catalytic converter temperature, which means that it is not a suitable method as it is not possible to provoke a change in the SCR catalytic converter operating range. The method can thus not be used for roadside inspections.
Figure 24: Cycle no. 3 where the vehicle is manipulated, i.e. the AdBlue emulator is connected.

Exactly the same pattern as in Figure 23 is shown, i.e. just an increase of NOx emissions at high idle, but at the same level as shown in Figure 23, which supports the conclusion that high idle is not a suitable control method.
Figure 25: Cycle no. 4 where the vehicle is not manipulated.

In cycle no. 4, the starting point is again a cooled SCR catalytic converter, which is disconnected by the ECU due to the temperature. On the chassis dyno, the vehicle goes through all the gears, which can be seen as peaks on the orange load curve. The first two acceleration tests show high NOx emissions, but in the third test, the temperature in the SCR catalytic converter is high enough for it to be activated. This is clearly shown on the blue curve showing NOx emissions. During the fourth acceleration, NOx emissions are stable at around 20ppm despite the fact that the SCR system must handle the many minor load changes following from gear shifts up through the load area.

The conclusion is that emissions measurement during acceleration may be considered as a potential control method, as the method after only three accelerations clearly shows if the engine emission control is actually working or has been disconnected.
In Figure 26 the acceleration test is repeated, but this time the AdBlue emulator is connected. During the test, only three accelerations were performed, but it is evident that NOx emissions remain at a high level. In this case, emissions are 25 to 30 times higher than when the vehicle was not manipulated, which supports the assumption that the method with three or four accelerations can be used as a control method.
Figure 27: Cycle no. 5 shows ammonia emissions during the entire test sequence.

When the AdBlue system is active, the injection of AdBlue is calculated continuously by the engine emission control. Any surplus AdBlue resulting from overdosage will presumably leave the system as ammonia. Control measurement of ammonia emissions, measured and reported over the course of the entire test sequence, shows an ammonia slip of less than 1ppm. The EU requirement for ammonia slip is 10ppm, which the vehicle complies with without problems. The low ammonia concentration in the exhaust during the entire test sequence leads to the conclusion that the ammonia test method has limited relevance as a control method.
4. Potential control methods

When choosing control methods, several parameters should be considered. The various control methods have pros and cons, which is why parameters such as time consumption for control, precision of control, access to equipment, costs of equipment and training of personnel should be assessed and rated before the most suitable control method for the task is selected.

Potential control methods can be divided into the following main groups:

1. Visual inspection
2. OBD/CAN bus reader
3. Vehicle emissions measurements
4. Remote sensing

The problem with several of the control methods is that they are often based on experience from previously detected fraud. The methods will therefore always be one step behind the development as you need to detect an AdBlue emulator before you can gather experience and detect more emulator devices of the same type. In the meantime, new and more sophisticated emulators, which cannot be detected in the same manner, are being developed.

![Flowchart](image)

**Figure 28: Detection of AdBlue emulators by means of visual inspection is one step behind the development.**

In order to break the "vicious circle", it would be preferable to select one or more control methods which combined will enable detection of all types of AdBlue emulators the first time they are seen, irrespective of whether it is a known product or a new model or method.
4.1. Visual inspection

Visual inspection of the vehicle is a widely used control method in Europe in general, where you look for physical installation traces during a roadside inspection. Cut wires, scotch-lock wire connectors, soldering, extra wires and connectors, as well as of course the physical box containing the AdBlue emulator are typical examples of installation traces.

The suspicion of a specific vehicle is for example reinforced by the following indicators:

- Missing fuses in fuse box
- Lack of fluid in the AdBlue tank
- The dashboard AdBlue level indicator shows either exactly ¼, ½, ¾ or full.
- Corrosion on AdBlue tank filler cap
- Unusual smell from AdBlue tank
- Inconsistent display of AdBlue level gauge
- Lack of AdBlue purchase receipts
- The temperature indicator on the dashboard shows -12°C or another value that does not match the current ambient temperature.
- Soot in the exhaust pipe on models fitted with particulate filter (Euro VI), because the particulate filter was removed when the AdBlue emulator was installed.
- After-market wiring and connections as well as connectors and hidden switches in the vehicle’s wiring.

The Danish traffic police has a guidance document, containing a detailed description of a brand-specific approach, which can be used during visual inspection of a vehicle. The procedure is not included in this report as the guidance document is updated continuously by the police so new types of AdBlue emulators are added in terms of physical installation traces and potential/likely locations of the emulator itself. This method does not guarantee that all emulators are detected, because conditions such as staff experience and the time available for inspection and detection of the more sophisticated emulator types are assessed to impact the success rate.

The visual inspection method is challenged by the fact that developers of AdBlue emulators develop smaller and more sophisticated products all the time. For example, tiny emulator boxes which are difficult to detect. Alternatively, it may be passive components, i.e. small potentiometers or resistors, simulating for example a low ambient temperature resulting in deactivation of the SCR system. The sophisticated products will therefore be physically smaller, and installing them in the wiring leaves few or no physical traces making it virtually impossible to determine if a vehicle is manipulated. Furthermore, in future, we expect to see the use of purely software-based manipulation, which consists in modifying the engine control unit, leaving absolutely no physical installation traces. Detecting this type of manipulation requires the use of other control methods. However, because such modification of the engine control unit requires specialist equipment and knowledge it is difficult to say how widespread the use of this type of manipulation will become.
**4.2. OBD/CAN bus**

An OEM or generic error code reader can be a helpful tool for detecting NOx manipulation, but using the equipment requires experience. It is estimated that detection of the more sophisticated AdBlue emulators, especially modification of the engine control unit, may be difficult with this equipment at this point in time.

In connection with laboratory testing at Danish Technological Institute, where the effects of AdBlue emulators on a vehicle were investigated (section 3), a representative from Scania Danmark attended the test, reading out error codes using Scania’s own brand-specific error code reader. With the emulator disconnected, the error code reader did not show any errors, but more surprisingly, no specific errors were reported when the emulator was connected either. Reading the error code reader results carefully, however, revealed that information on the entire engine emission system was missing from the error report, which is a clear indication that the vehicle is fitted with an emulator. Therefore, the error code operator must be very alert and possess some knowledge of which information the error code reader must report on a manipulated versus a non-manipulated vehicle.

The error code reader had a feature called "engine live data" also called "flight mode". Using this feature, it is possible to monitor the individual components of the engine emission control, e.g. AdBlue injector, temperature and NOx sensors, during operation. With the right knowledge and experience, the feature enables detection of an emulator or passive components, because a conditioned SCR catalytic converter requires central components such as the AdBlue injector to be active. Furthermore, system temperature levels can be monitored to check if they correspond with actual conditions.

In addition to the brand-specific error code readers, a number of after-market, more generic error code readers are available on the market. We have had a dialogue with Niels Ezerman, who owns the company NEtech autoteknik, supplying diagnostics equipment to garages. The company states that it does not supply error code readers to specifically detect manipulated vehicles, but says there are three scenarios in which an emulator can be detected.

1. No contact with the AdBlue system as communication is blocked/taken over by the emulator. Easy to detect, as the error code reader does not report information from the AdBlue system.
2. The AdBlue system data is mentioned in the error report, but the system is suspected to be provided with an emulator blocking for AdBlue injection by means of a "gateway". The solution to this is to operate the vehicle while the error code reader is connected in "engine live data mode" to monitor that the system is functioning.
3. The most advanced types, e.g. modifying the engine control unit, which do not leave any immediate digital traces. Currently not possible to detect with NEtech’s error code readers. It requires advanced CAN bus readers capable of interpreting the internal data architecture used by the AdBlue software to decode and document emulated CAN bus messages.

The use of equipment from NEtech for detection of manipulated vehicles is therefore fully in line with our experiences with the Scania error code reader.
4.3. Vehicle emissions measurements

Based on the laboratory testing results on the documentation of an AdBlue emulator’s effect on a vehicle, it is clear that there is a significant difference between emissions from a vehicle with and a vehicle without AdBlue emulator installed. Vehicle emission measurement is estimated to be an essentially reliable method for detecting NOx manipulation. However, several preconditions must be met for the method to be applicable:

- Emulator must be connected
- Motor and SCR catalytic converter must be at operating temperature
- The vehicle must be under load or accelerating, which means that a test distance is required
- You need access to portable emissions measurement system with the correct measuring range for NOx and temperature

Based on the results in section 3.5 of this report, the following comments apply to the procedures:

Constant load:

1. The vehicle is pulled over, operating temperature is secondary
2. The vehicle is loaded on the test distance or chassis dyno
3. NOx measurement is performed after the SCR catalytic converter

Measurement during idling:

1. The vehicle is pulled over with conditioned engine and engine emission control
2. The engine is idled until the temperature drops (only diesel)
3. NOx measurement is performed after the SCR catalytic converter
4. When the flue gas temperature reaches approx. 250°C, the normal SCR will disconnect and a significant increase in NOx emissions should be seen

A key condition of the method is that the engine emission control must actually be conditioned when measurement starts, because you would otherwise not see the expected change and increase of the NOx level after the SCR catalytic converter.

High idling, corresponding to NOx measurements performed at periodic inspection centres on petrol passenger cars:

We have investigated if it makes sense to measure NOx using the same method as is applied at periodic inspection centres, where the passenger car is left in neutral while idling rpm is increased. The method is not suitable, as idling or even high idling just cools down the engine emission control thus eliminating the basis for measuring the functionality of the engine emission control.

Measurement during acceleration equivalent to environmental periodic inspection:

1. The vehicle is pulled over, operating temperature is secondary
2. Four successive accelerations are performed from standstill to approx. 70km/hour on a test distance
3. NOx is measured at the exhaust using portable equipment

The method is suitable as the acceleration ensures heating of the engine emission control bringing it to operating condition. The engine emission control so to speak “returns with
emissions” corresponding to the vehicle’s Euro class. A potential procedure for acceleration testing could be based on the current environmental periodic inspection programme, which has, however, been developed for buses but which could be adjusted to trucks if a suitable procedure for location of measuring equipment, vehicle load, gear switching pattern, etc. is developed. We propose considering the new TID method [30] or the SEMS method [31] developed by the company Techno-Matic.

**Ammonia slip measurement**

When injecting AdBlue into the engine emission control, sometimes an overdosage occurs, resulting in surplus AdBlue fluid being released from the system as ammonia. Ammonia is considered harmful to the immediate environment, which is why most vehicles are equipped with a so-called ammonia slip catalytic converter, which effectively converts ammonia to nitrogen and water. Ammonia slip measurements were performed on the vehicle while on the chassis dyno, and no measurable ammonia slip was detected at any operating point or during any load or gear change. The method is thus not applicable.

**4.4. Remote sensing**

Remote sensing is a more newly developed emission measurement method. It differs from traditional measuring methods where you extract and measure exhaust concentrations directly from the vehicle in that you measure the exhaust composition in the vehicle’s slipstream.

The core of the measurement method is that during combustion of diesel fuel there is a variable but fairly predictable relationship between the gases NOx and CO2. As the density of both gases is approximately the same, they are diluted at the same rate in time with the distance from the exhaust pipe. Therefore, the volume ratio between the two gases will be constant both close to and at a distance from the exhaust pipe until the gases are mixed with the gas from other vehicles or are diluted in the atmosphere to an extent which makes measuring impossible.

The NOx/CO2 ratio should be maximum 1:3,000 for Euro V-compliant trucks and as low as 1:10,000 for Euro VI-compliant trucks. The Euro class is easily determined by means of the number plate, the environmental badge on the vehicle’s windscreen or the truck’s data plate.

The atmospheric CO2 content is approx. 450ppm. The meter should therefore have a scale from 0-1000ppm. The NOx sensor must have a resolution of 0-1ppm.

To document these numbers, we have included an illustration of the NOx and CO2 ratio in the measurements performed by the Institute of the Euro VI-compliant truck during load tests with and without the AdBlue emulator connected.
Figure 29 shows the CO2/NOx ratio without the emulator connected, i.e. the vehicle is working as intended with emissions compliant with the Euro VI standard.

In Figure 29, you can see that the NOx/CO2 ratio is in the range 1:2000-4000 at the load points measured, however, with clear fluctuations in connection with load changes that would also occur naturally when driving on the road. Please note that the NOx/CO2 ratio of 1:10,000 expected for Euro VI-compliant vehicles is only attainable when the AdBlue system has reached the right operating temperature, which is evident from the figure. At the curves’ starting points, the AdBlue system operating temperature is too low for the system to be activated, resulting in a NOx/CO2 ratio of approx. 1:40.

At the same time, please note that the NOx/CO2 ratio is highly dependent on the vehicle’s load point as the CO2 content varies greatly in time with the actual engine load. It is only when the vehicle is working at full load that the CO2/NOx ratio is around 1:10,000. In the tests illustrated in Figure 29, the 180kW correspond to approx. 60% engine load, which explains the CO2/NOx ratio of 1:approx. 4,000.
Figure 30: The CO2/NOx ratio with the emulator connected. In this operating situation, the vehicle’s emission levels are found to be similar to those of a Euro I-compliant vehicle.

Remote sensing can be divided into two main areas:

1. Stationary remote sensing where the equipment is placed on the side of the road
2. Portable remote sensing where the equipment is placed in the control authority’s vehicle

Simultaneous measurement of NOx and CO2 on the side of the road (stationary remote sensing) combined with scanning of number plates of passing vehicles is a method used in Sweden. It has been possible to estimate NOx emissions per litre of fuel from each passing vehicle. The method can be used to get an indication of which types of vehicles may be manipulated. The advantage of this method is that it is possible to check a large number of vehicles. After having spotted potentially manipulated vehicles, they must, however, still be pulled over for further inspection.

Mobile remote sensing has been tested in Germany. The University of Heidelberg under Professor Denis Pöhler have devised a method for measuring exhaust gasses in the slip-stream of moving trucks. The advantage of this method is that the vehicle measured is operating at a load point, which according to the above figure should result in significant fluctuations if the vehicle is manipulated. Provided that the driver does not spot the control
authority's vehicle, it must be assumed that the emulator is active if such is installed on the vehicle.

A more detailed description of remote sensing is included in the Danish Environmental Protection Agency's project [28]

5. Neighbour check

We have contacted a number of researchers and authorities in different EU countries as listed in Table 1. A fixed list of questions was used:

1. Have you seen any examples of illegal devices found on trucks driving through your country?
2. Which methods do you use to detect and remove illegal devices?
3. Do you have any national programmes or working groups investigating this type of fraud?
4. Which methods are used for roadside inspection specifically regarding NOx emissions?

Can I have your contact details in case I need more information from you?

In addition to asking the above questions, a literature search was conducted using review of available reports and online searches.

<table>
<thead>
<tr>
<th>Country</th>
<th>Status</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>In Sweden, the control authority is the Swedish Transport Agency (vehicle inspection) or the Swedish Police. Different types of NOx emulator devices have been detected in roadside inspections. Recent years have shown examples of legal proceedings involving Swedish as well as foreign trucks in Sweden. The proceedings can be followed online. In Sweden, a procedure describing suitable methods for detecting NOx manipulation remains to be produced. It was also reported that no actual national programmes exist on the subject, but that the issue is handled in the individual Swedish police regions. Only visual inspection is used as no actual emission measurement equipment to support police work is available. When vehicles are called for periodic inspection, any emulator devices will of course have been removed. That is why the inspection responsibility in practice lies with the Swedish police. City of Stockholm states that no checks of the functionality of AdBlue systems and emissions are performed. City of Stockholm usually requires companies supplying services to City of Stockholm to meet applicable laws and Stockholm’s environmental regulations for heavy traffic as well as comply</td>
<td>[4] [6] [7] [8] [9] No response: [10]</td>
</tr>
</tbody>
</table>
with ISO 14000 and 9000. The operators are assumed to perform the stipulated, necessary inspections themselves.

City of Stockholm refers to the Swedish Association of Road Transport Companies, which make statistics in this area. http://www.akeri.se/
However, a search on the website, did not yield any information on specific initiatives in this area.

Norway

Information from the Norwegian Public Roads Administration suggests that a lot of work has gone into preparing procedures to detect NOx manipulation. Answers from the Norwegian Public Roads Administration (Statens Vegvesen) are included below (translated from Norwegian):

Our inspection centre in Svinesund, on the southern part of the border between Norway and Sweden, has performed inspections targeted at AdBlue emulators on several occasions. On these occasions, one to two people were assigned to the task, and they were able to inspect up to ten vehicles a day. Of the vehicles satisfying the criteria for closer inspection (visual inspection, conversation with the driver, etc.), emulators were detected on more than 50% of the vehicles. We also believe that the total percentage of vehicles with emulators installed could be as high as 10-20%. It is difficult to determine, because
a) we only detect emulators/boxes, not direct reprogramming of ECU
b) some emulators/boxes are better hidden than others and we do not know if our searches uncover all boxes.

We detect emulators in Norwegian as well as foreign (mostly foreign) vehicles, and mostly in Euro V-compliant vehicles, but also in Euro VI-compliant vehicles. We have detected more than 60 emulators in total (numbers from before the summer holidays).

In Norway, we detect emulators by inspecting vehicles that are sent for inspection in Svinesund. We start with a visual inspection of the exhaust pipe. If soot is detected, we look at the AdBlue level gauge, the AdBlue tank and tank filler cap. A dirty tank filler cap and an apparently empty tank or an actual tank level that does not correspond to the dashboard level gauge are all indications of foul play. If the driver cannot tell us when/where he topped up last, the vehicle is sent for further inspection.

The inspection is performed by removing the covers in front of and behind the vehicle's control panels and checking all wires to see if they lead to an emulator. In general, we do not have the authority/power to remove such boxes. An inspection report is issued on the vehicle.

We have a team working with this area at the Norwegian Road Directorate. I have also been present during inspections performed in Svinesund. Danish traffic police also attended the inspection.
In general, we comply with the EU directive on technical roadside inspections (visual inspection). We assess if other equipment is required, and we have looked into some of the equipment presented to us by the Danish traffic police (AdBlue meters/OBD data connection equipment). We measure NOx levels on busy roads, but these measurements are not related to specific vehicles.

Norwegian police have received our questions and have replied that they will be answered by "Utrykningspolitietets fag- og metodeavdeling," but we have not heard anything back from the yet.

No response:

<table>
<thead>
<tr>
<th>Germany</th>
<th>German television has covered NOx manipulation of trucks in an in-depth documentary.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As a result of roadside inspections, The Federal Office for Goods Transport (Bundesamt für Güterverkehr BAG) has become aware of the use of AdBlue emulators. Compliance with the rules and regulations in the area is monitored by BAG and the German police. AdBlue emulators have been detected in connection with the so-called technical roadside inspections. The challenge is that the emulators have to be detected by means of visual inspection, which make demands on the inspectors’ skills and experiences locating and detecting deliberate manipulation. Driving with an AdBlue emulator installed is an offence punishable by fine and may result in the haulier losing his operating licence. The vehicle may not be operated again until it has been brought back to its original legal state. Furthermore, manipulation of the AdBlue system constitutes an offence as the rate of duty paid for the emission class does not correspond with the actual emission levels. In order to achieve the best possible results of the inspections, BAG regularly exchanges information with federal authorities, and joint inspections are performed with the police authorities of the individual German Länder.</td>
</tr>
<tr>
<td></td>
<td>No response: [12]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Switzerland</th>
<th>VERT has proposed the control method TeVeNOx – test type 3. The method consists of a simple function test of the AdBlue system. The method requires conditioning of the engine to a temperature where the AdBlue system is automatically activated. The engine is then cooled to a temperature where the AdBlue system is automatically deactivated. Throughout the test sequence, the NOx concentration in the exhaust gas is measured using recording equipment. The recommended method for heating the engine requires either a mechanical chassis dyno or a test distance, where the engine can be exposed to a constant load. The load must correspond to travelling at a speed of 40-50 km/h. Cooling is done with the engine at idling speed for 10-15 minutes. Some trucks automatically deactivate the AdBlue system when the truck is stationary. Therefore, the wheels of the truck should rotate slowly while the engine is cooling.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[13][14]</td>
</tr>
<tr>
<td></td>
<td>No response: [15][16]</td>
</tr>
<tr>
<td></td>
<td>[17]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td></td>
<td>[18][19]</td>
</tr>
<tr>
<td></td>
<td>[20][21]</td>
</tr>
<tr>
<td></td>
<td>[22][23]</td>
</tr>
<tr>
<td></td>
<td>[24][25]</td>
</tr>
</tbody>
</table>
Extensive research has been carried out, and procedures for both roadside inspection and laboratory testing have been prepared.

Switzerland is also one of the countries where continuous inspection of a large part of the trucks crossing the country is carried out. Inspections are performed in so-called HTCCs, Heavy-duty Traffic Control Centres. At HTCC Erstfeld they inspect approx. 40,000 trucks a year. Last year, 108 manipulated vehicles were identified among 15,500 inspected vehicles. The authorities have come quite far preparing a guideline called “AdBlue Betrug: Manipulationen der Abgasnachbehandlung” (in English: AdBlue fraud: manipulating exhaust after-treatment), which is a guideline describing how to detect AdBlue manipulation. We have written the author Othmar Arnold at the Uri canton police, requesting insight into their manual, and we have subsequently received a copy of the manual they use.

Table 1 Overview of implemented neighbour check and the results thereof

<table>
<thead>
<tr>
<th>Country</th>
<th>Response</th>
<th>Further Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>No response was received from Austria</td>
<td>No response: [27]</td>
</tr>
<tr>
<td>England</td>
<td>A kind of practice has been prepared, applying visual inspection supported by OBD error code readers.</td>
<td>[28]</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>RDW has acknowledged receipt of our email, but we have not yet received a response.</td>
<td>No response: [38]</td>
</tr>
<tr>
<td>Poland</td>
<td>It has not been possible to establish contact to authorities in Poznan.</td>
<td>No response: [39]</td>
</tr>
<tr>
<td>Lithuania</td>
<td>We found two local providers. Both provided brand-specific emulators (i.e. MAN, IVECO, DAF, etc. – so their emulators do not work with all brands).</td>
<td>[46]</td>
</tr>
<tr>
<td></td>
<td>Re. price: One provider uses a site corresponding to the Danish Den Blå Avis (similar to eBay), and the price range is EUR 80-100. The other provider does not state any prices.</td>
<td></td>
</tr>
<tr>
<td>Bulgaria</td>
<td>A local contact has asked a Bulgarian haulage contractor, and emulators are also used in Bulgaria.</td>
<td>[47]</td>
</tr>
<tr>
<td>EU</td>
<td>A guideline regarding NOx manipulation has been prepared.</td>
<td>[48]</td>
</tr>
</tbody>
</table>

Reviewing the international material, we found that visual inspections are still the prevalent method used to detect NOx manipulation. Generally speaking, Switzerland is the country which applies the most advanced control methods. This is no surprise as Switzerland has been leading within control of filters and catalytic converters for years, partly due to the VERT scheme. Switzerland is also a country with many road tunnels, which is the main reason for their strong emphasis on correct functioning exhaust filters.
The EU Commission has issued a guidance note [48] to member states on how best to deal with NOx manipulation of cars and trucks. The guidance note is useful in connection with type approvals, but is of less use to the police.
6. Pricing

The public transportation company Movia has calculated key operating costs for buses after retrofit of SCRT systems as required under the Clean Air for Denmark programme. The costs range from DKK 1.5-3.5/hour when everything is included – i.e. ammonia consumption, service and time for replacement of canisters \[^{32}\]. In the following, we have chosen to calculate the annual cost distributed on operating costs, i.e. purchase of AdBlue, and service costs, i.e. repairs and replacement.

6.1. AdBlue operating costs

In the German documentary "Die Lüge vom sauberen LKW" (in English: The myth of clean trucks) by Christian Bock, it is stated that an AdBlue emulator can save the haulier up to EUR 2,000 a year, corresponding to DKK 15,000.

The documentary states that the price of AdBlue is EUR 0.40/litre, corresponding to DKK 3/litre exclusive of VAT. However, Danish fuel companies state a price of approx. DKK 4.73/litre exclusive of VAT.

According to German information, a truck typically consumes 1.6 litres of AdBlue per 100km. At Danish prices, this will amount to DKK 7.57 per 100km.

Provided that the truck has an annual mileage of 150,000km, the potential annual savings amount to DKK 11,355 exclusive of VAT.

This must be compared to the cost of the AdBlue emulator of only approx. EUR 600, corresponding to DKK 4,500 plus installation. The price of the cheapest editions is as low as EUR 80, corresponding to almost DKK 600 plus installation.

<table>
<thead>
<tr>
<th>TCO module</th>
<th>AdBlue only</th>
<th>AdBlue docing percentage</th>
<th>2%</th>
<th>4%</th>
<th>6%</th>
<th>8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual driving [km]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.000</td>
<td>kr.</td>
<td></td>
<td>1.410</td>
<td>2.819</td>
<td>4.229</td>
<td>5.638</td>
</tr>
<tr>
<td>80.000</td>
<td>kr.</td>
<td></td>
<td>2.819</td>
<td>5.638</td>
<td>8.457</td>
<td>11.276</td>
</tr>
<tr>
<td>120.000</td>
<td>kr.</td>
<td></td>
<td>4.229</td>
<td>8.457</td>
<td>12.686</td>
<td>16.914</td>
</tr>
<tr>
<td>150.000</td>
<td>kr.</td>
<td></td>
<td>5.286</td>
<td>10.572</td>
<td>15.857</td>
<td>21.143</td>
</tr>
</tbody>
</table>

Figure 32: Annual costs of AdBlue at different mileages and at different AdBlue consumption rates.

In order to check the German numbers, we have made our own calculations of different AdBlue consumption rates as shown in Figure 32. The calculations include only the costs of AdBlue and do as such not consider potential savings on service and maintenance of the SCR and AdBlue systems. Based on information from DTL \[^{33}\], calculations have been made considering AdBlue consumption rates of up to 8%. In particular the Euro VI-compliant vehicles require a high percentage of AdBlue of up to 8-9% under some operating conditions.
6.2. Cost of service and repair

The company MT filter service in Karlslunde, Denmark, has experience servicing and repairing NOx catalytic converters. The company states that there is generally no need to perform service of the SCR part of the system. SCR systems have an extensive service life of typically eight to ten years. However, the service life varies with the mileage, and the service life may be reduced by e.g. oil pollution due to an engine defect. If pollution occurs, the SCR catalytic converter needs replacing.

After eight to ten years, large deposits will have formed inside the catalytic converter, and they cannot be removed by traditional methods. Therefore, replacement or repair is required.

On the slightly older Euro IV- and Euro V-compliant vehicles, it is possible to repair the SCR catalytic converter by replacing the core in a specialist garage. The cost is approx. DKK 20,000. If, on the other hand, the catalytic converter is to be replaced by a new OEM SCR catalytic converter, the cost is approx. DKK 45,000.

For Euro VI-compliant vehicles, the situation is more difficult, as repair of the catalytic converter is not always possible.

The following standard prices [35] are used for subsequent TCO calculations applicable to Euro VI-compliant trucks:

- NOx sensor: DKK 4,300
- AdBlue pump: DKK 10,000
- SCR control unit: DKK 8,000
- SCR catalytic converter: DKK 51,000

6.3. Total cost of ownership

The total cost of operating a Euro VI-compliant truck is calculated by means of the Total Cost of Ownership tool, developed in the project “Analyse af Rammevilkår for gas i tunge køretøjer” (in English: Analysis of the framework conditions for emissions from heavy-duty vehicles).

Using this program, we have calculated scenarios for different AdBlue consumption rates while including service and maintenance costs.

![TCO calculation of annual AdBlue and service costs at different mileages and at different AdBlue percentages.](image)

As can be seen from the TCO calculations, the cost of service and maintenance has a significant impact on the total operating costs of an engine emission control system. The
costs are affected by particularly the significant costs of replacing the SCR catalytic converter, which must be assumed to be another incentive for installing an emulator which thereby postpones or eliminates these costs.
7. References

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20. SAE 2014-01-1569. Testing of SCR-Systems on HD-Vehicles-TeVeNOx
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31. TM SEMS: EPA record no.: 141-01397.
32. Personal contact: Joachim Reinhard Danchell, Movia
33. Email correspondence with DTL, Finn Bjerremand, who has informed us of the typical AdBlue consumption based on information from three different truck manufacturers.
34. MT Filterservice Aps. Contact by telephone to CEO Flemming Nøhr
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38. RDW (Rijksdienst voor het Wegverkeer)
39. Policja Ruchu Drogowego
40. Applus+ RTD
41. TÜV
42. Transport Agency Sweden • Statens vegvesen, Regelverk for lavutslipssonær Norway
43. Port of Rotterdam authority
44. Municipal Roads in Poznan
45. TfL (Transport for London)
46. Lithuania, Raivis
47. Bulgaria, Dimitar
8. Definitions and abbreviations used

- AdBlue: Trade name of the fluid (reactant) used in the AdBlue system. AdBlue is an aqueous solution containing 32.5% urea and 67.5% demineralised water.
- AdBlue system: The NOx-reducing unit in the engine emission control. Consists of SCR catalytic converter, dosing pump, control arrangement and AdBlue tank.
- SCR catalytic converter: Selective Catalytic Reduction. (The actual NOx catalytic converter, converting NOx into harmless nitrogen and water)
- NOx: The sum of the two gases NO and NO2, which are inevitably produced during combustion of fuel in a combustion engine.
- DPF: Diesel Particulate Filter (filter, removing up to 99% of particulates in vehicle exhaust)
- Emulator: Electronic device that mimics the functionality of another device.
- OBD: On-board Diagnostics. (data communication with the vehicle, which among other things enables readout of error codes)
- ECU: Engine Control Unit. The engine's central control unit.
- EEC: Engine Emission Control. The emission system control unit.
- OEM: Original Equipment Manufacturer.