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CARES

CITY AIR REMOTE EMISSION SENSING

D1.2 – Monitoring of vehicle tampering

WP1
Task 1.4
Deliverable 1.2

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Summary

1. Vehicle after-treatment systems were tampered during the vehicle emission characterisation experiments conducted at the test track. The ability of three remote emission sensing techniques to detect tampering of the after-treatment systems and quantify changes in emissions behaviour was investigated.

2. The selective catalytic reduction (SCR) systems of three vehicles were switched off to replicate vehicles with SCR emulators installed. For the three remote emission sensing techniques, average NO_x/CO_2 ratios were calculated for each test session and used to predict the state of the SCR system.

3. The total number of predictions made for the state of the SCR system was plume chase (PC) > point sampling (PS) > remote sensing (RS). This is expected because PC measurements typically last several minutes whereas PS measurements last several seconds and RS measurements < 1 s. The detailed information obtained by PC is valuable for monitoring vehicle after-treatment system tampering, although fewer vehicles can be measured than PS and RS in a certain period of time.

4. A greater number of SCR tampering predictions were made for the truck compared to the Caddy and Transporter across all 3 remote emission sensing techniques. This can be attributed to the higher NO_x/CO_2 ratios and increased difference in emissions between SCR system on and off.

5. All of the SCR tampering predictions made for the truck were correct, with the exception of 2 predictions per measurement technique. The incorrect predictions occurred when the SCR had recently been switched on or off at the start of the test session, causing a delay in the NO_x emission changes. This resulted from the time required for the SCR system to reach optimum temperatures when it was first switched on, or residual diesel exhaust fluid available to reduce NO_x when it was first switched off. This was an effect of the experiment design and is unlikely to be encountered during real world measurements.

6. All predictions made for the Caddy were correct with the exception of 1 prediction made based on the RS measurements. This was attributed to the potentially low NO_x/CO_2 ratios under constant speed driving conditions, despite the fact that the SCR was tampered. For the Transporter, 2 incorrect predictions were made based on the PC measurements and 1 based on the PS data. Despite this, PC measurements still provided an overall greater number of correct predictions for each test vehicle.

7. There was normally a specific reason why an after-treatment prediction was incorrect. For example, cold start emissions may be falsely interpreted as SCR system tampering. The benefit of PC compared to PS and RS in this situation is that the reduction in emissions with time can be tracked throughout the vehicle chase, and false positives can be avoided.

8. Incorrect predictions may also occur when measured emissions are influenced by a high emitting vehicle driving in front of the vehicle of interest. For PC, it is possible to avoid these situations, by not measuring a vehicle that has a HDV driving in front of it, and not performing measurements on busy roads. Careful analysis of PS and RS vehicle pass information may also be useful for identifying situations when the measured emissions are influenced by emissions from other vehicles.

9. Although there were a greater number of measurements assigned as valid for RS compared to PS, there was more variation in the RS NO_x/CO_2 ratios for each test session. This made it more challenging to predict the state of the SCR system. The relationship between sample size and the 95% confidence intervals in the mean for SCR system on versus off were compared for RS and PS. Fewer valid PS measurements are needed for a statistically significant difference between tampered and untampered NO_x emissions to be observed at the 95% confidence level. However, it may take more time to obtain a certain number of valid measurements using PS than RS.

10. A diesel particulate filter (DPF) bypass was installed in the Caddy and the DPF was tampered by opening the bypass. Particle number (PN) and black carbon (BC) emission factors were derived using a range of fast response analysers and used to predict DPF tampering.

11. For most sessions the DPF state could be correctly identified in the case of PS and PC. It was challenging to predict whether the DPF bypass was open or closed due to the low particulate emissions from the Caddy, even when the DPF bypass was open. For PS, if the PN and BC emissions were consistently above the instrument detection limits, the DPF was correctly predicted to be tampered, and if the PN and BC emissions were not detected during a particular session, the DPF was assigned as operating normally. For PC, the 90 nm SMPS PN emission factors were used to predict DPF tampering, based on an emission threshold of 5×10^{11} particles per kilogram of fuel.

12. The UV opacity measurements obtained using the commercially available remote sensing device did not show a statistically significant difference for DPF bypass open versus closed; however, opening the the Caddy DPF bypass had a subtle effect on particulate emissions and remote sensing may be able to detect more significant increases in particulate emissions when a DPF is fully removed.

13. In the future, it would be useful to measure a wider range of vehicles and evaluate PN and BC emission factors obtained when the DPF is operating normally compared to when the DPF has been removed. This would help to establish PN and BC emission thresholds for detecting DPF removal under real world driving conditions.

Attainment of the objectives and explanation of deviations

Description of work related to deliverable as given in DoW

This report builds on the main findings of D1.1 and specifically addresses how the CARES measurement approaches can be used to detect tampering of vehicle after-treatment systems. The ability of the different remote emission sensing techniques to detect tampering of selective catalytic reduction systems and diesel particulate filters and quantify the associated changes in emissions is explored.

Time deviation from original DoW

16 months.

Content deviation from original DoW

None.

Contents

1 Introduction

1.1 Background

The focus of D1.1 (*Measurement technology intercomparison and evaluation*) was to assess the performance of a range of vehicle emission measurement techniques used during controlled characterisation experiments at a test track located in the Netherlands. Individual vehicle measurements of different pollutants were compared across a wide range of vehicle operating conditions, and factors affecting data capture success rates were explored. This report, D1.2 *Monitoring of vehicle tampering*, builds on the main findings of D1.1 and specifically addresses how the CARES measurement approaches can be used to detect tampering of vehicle after-treatment systems. The changes in emissions behaviour associated with tampering the following types of after-treatment systems are investigated:

- **Selective catalytic reduction (SCR) systems**. SCR systems are used to minimise NO_x emissions from vehicles by using NH_3 to convert NO_x to nitrogen gas and water. NH_3 is generated from the decomposition of urea present in the diesel exhaust fluid required to operate vehicles with SCR systems. A SCR emulator is a device that simulates a functioning SCR system by overriding the controls of the on-board SCR system. The same signals are sent to the engine control as the original SCR system, but the NO_x emissions are not controlled. Despite being illegal in Europe, vehicle owners may choose to install a SCR emulator to avoid the costs associated with the diesel exhaust fluid or repair of the SCR system. In this study, NO_x/CO_2 ratios when the SCR system is switched on and off are compared, to investigate whether point sampling, remote sensing and plume chase techniques have the potential to detect the use of SCR emulators under real driving conditions.
- **Diesel particulate filters (DPF)**. DPFs operate by trapping particles from the engine exhaust. The soot is collected on the filter and periodically the DPF is regenerated by burning the soot at very high temperatures. During their lifetime DPFs degrade and can become defective e.g. due to uncontrolled filter regeneration events [1]. In some cases, motorists may opt to remove their DPF and drive illegally without it, to avoid paying for maintenance costs or a replacement filter. The ability of commercially available remote sensing devices to detect vehicle particulate emissions is based on an UV opacity measurement and provides a limited amount of information. Fast-response particle number (PN) and black carbon (BC) analysers have the potential to provide more detailed information on particulate emissions. In this report, the PN and BC mass concentrations from a range of particle instruments are evaluated, to assess whether they can be used to detect DPF removal under real driving conditions.

1.2 Aims

The main aims of this report are to:

1. Quantify changes in measured emissions when the SCR system is switched on/off and the DPF bypass is open/closed. Compare the predicted state of the after-treatment

system, provided by the instrument operator, to the known state of the after-treatment system.

2. Evaluate whether the state of the after-treatment system can be correctly predicted using different remote emission sensing techniques and investigate reasons why the state of the after-treatment system may be falsely interpreted.

3. Consider the advantages and limitations of the different remote emission sensing measurement techniques for detecting vehicle tampering and make recommendations for monitoring vehicle tampering under real driving conditions.

2 Methods

2.1 Measurement location

A series of emission characterisation experiments were carried out as part of the CARES project, to evaluate the capability of a range of remote emission sensing technologies. The experiments were conducted at Rijkdienst voor het Wegverkeer Test Centre Lelystad (TCL), an independent test laboratory for vehicle technology. TCL is located 15 km southeast of Lelystad in the Netherlands (Lat. 52.46, Lon. 5.51), in an isolated location away from major emission sources. This type of environment is ideal for controlled characterisation experiments due to the stable background and minimal interferences from other emissions in the local vicinity.

2.2 Experimental design

Vehicle emission measurements were performed on a 2.8 km circuit test track. Six test vehicles, selected to be representative of wider vehicle fleets, were driven around the track multiple times. The PC vehicle followed a specific test vehicle for each lap of the track. The PS and RS instrumentation was set up in an additional lane on the inner side of one of the straight sections of the circuit. For each lap, all test vehicles and the PC vehicle diverted off the main track and past the PS and RS equipment. A total of 1,435 vehicle passes were recorded. The measurements were conducted in daylight hours during periods of dry weather.

A program of experiments was carefully designed to evaluate the performance of the different technologies under a wide range of driving conditions. A total of 21 sessions were planned, for which each vehicle was driven around the track multiple times, to obtain repeat measurements under the same driving conditions. This included a series of constant speed tests, with different combinations of vehicle speeds on the main track and the additional PS/RS test lane. The different vehicle speeds on the main track were 30, 50, 80, 100 and 120 $km\,h^{-1}$ and the speeds on the PS/RS test lane were 30, 50 and 80 $km\,h^{-1}$.

A range of 'acceleration from standstill' tests were performed; a convoy of vehicles (6 test vehicles, 1 PC vehicle) waited at a cone which was placed either 8 or 30 metres before the PS/RS setup, and in turn, each vehicle accelerated from standstill past the PS/RS equipment before travelling around the remainder of the track at a designated speed. Two acceleration types were tested, defined as 'normal' and 'sporty' acceleration. For both the constant speed and acceleration tests, the time delay between each vehicle was approximately 20 seconds. To study the ability of different instruments to distinguish emissions from individual vehicles travelling closer together, a second set of acceleration from standstill tests were performed, in which the time delay between each vehicle was either < 2 s, 4 s, 7 s or 10 s.

The order of the test vehicles was varied systematically throughout the program of experiments, to assess the influence of different combinations of vehicle order on measured emissions. For example, this meant that the influence of emissions from a nearby high-emitting vehicle on the measured emissions of a low-emitting vehicle could be studied. The position of the PC vehicle was also changed regularly to ensure that PC measurements were obtained for the full range of test vehicles under different driving conditions. This report will focus on whether the different measurement techniques can be used to detect and quantify vehicle emission tampering. The state of the after-treatment technologies was modified throughout the experiments, as described in more detail in sections 2.5 – 2.6.

2.3 Instrumentation

A full description of the instrumentation can be found in D1.1, section 2.4. In brief, 'traditional' vehicle emission remote sensing measurements were carried out using the commercially available Opus RSD 5500. The plume chase instrumented van, used to follow and sample the exhaust plume from a target vehicle, was equipped with a range of fast-response analysers for the measurement of NO_x (NO and NO_2), CO_2 and particle number. A range of fast-response instruments for the measurement of NO_x, CO_2, black carbon mass and particle number were placed by the side of the track as point sampling devices, to measure individual plumes of passing vehicles.

2.4 Test vehicles

Table 1 shows the vehicle technical information for the six test vehicles used for the emission characterisation experiments. The vehicles were selected to be representative of wider vehicle fleets.

Table 1: Vehicle technical information for the six test vehicles used at Test Centre Lelystad.

Vehicle	Category	Manufacturer	Fuel type	Euro class
NMAX Scooter	L3	Yamaha	Gasoline	5
MT-07 Motorbike	L3	Yamaha	Gasoline	5
Touran	M1	Volkswagen	Gasoline	5J
Transporter	M1	Volkswagen	Diesel	6
Caddy	N1	Volkswagen	Diesel	6
F-Max Truck (+ trailer)	N3 (O4)	Ford (Krone)	Diesel	VI

2.5 Modification of after-treatment systems

To assess the ability of the different vehicle emission measurement technologies to detect and quantify vehicle emission tampering, the SCR systems installed in the Ford F-Max truck, VW Caddy and VW Transporter were switched on and off throughout the test track experiments. Furthermore, the VW Caddy was fited with a small DPF bypass which could be opened and closed. When the bypass was closed, the DPF was operating normally and when the bypass was opened, the DPF was considered tampered. In this study, we investigate the ability of different particle analysers to distinguish emissions when the the DPF bypass is opened and closed. However it is important to note that opening the DPF bypass caused a more subtle increase in particulate emissions than would be expected when the DPF is fully removed from a vehicle.

Four combinations of vehicle after-treatment conditions were designed for the three test vehicles that were modified, as summarised in Table 2. ‘0’ refers to when the after-treatment system is operating normally, i.e. the SCR system is switched on, or the DPF bypass is closed, and ‘1’ indicates that the after-treatment system is tampered (SCR switched off, or DPF bypass open).

Table 2: After-treatment system combinations for the VW Transporter, Ford truck and VW Caddy. ‘0’ refers to normal conditions (SCR switched on or DPF bypass closed) and ‘1’ refers to tampered conditions (SCR switched off or DPF bypass open).

Condition	**Transporter SCR**	**Truck SCR**	**Caddy SCR**	**Caddy DPF**
C1	0	0	0	0
C2	1	1	1	1
C3	0	1	1	1
C4	1	0	0	1

2.6 Emission thresholds for after-treatment system tampering

The instrument operators were requested to independently analyse their data sets and provide emissions expressed as a ratio of the amount of pollutant to CO_2, for each vehicle pass or vehicle chase. Throughout the experiments, those responsible for operating the remote emission sensing instrumentation were not informed of the vehicle after-treatment system conditions described in Table 2. This blind testing approach ensured that the instrument operators were not influenced by knowing the state of the vehicle after-treatment system when analysing the data. For each experiment session, a prediction of the state of the SCR system was requested from each person who analysed the NO_x data and a prediction of whether the Caddy DPF bypass was open or closed was requested from each person who analysed PN or BC data.

A series of emission thresholds were established to predict whether a vehicle’s SCR system was switched on or off. Table 3 shows the NO_x emission thresholds used for the PC vehicle emission measurements. Light duty vehicles (LDVs) with NO_x/CO_2 ratios between

1.3 and 2.0 ppb/ppm were considered 'suspicious', i.e. the SCR system *may* be switched off, and LDVs with NO_x/CO_2 ratios greater than 2.0 ppb/ppm were designated as tampered, i.e. the SCR system is switched off. A similar approach was adopted for heavy duty vehicles (HDVs); NO_x/CO_2 emissions between 1.7 and 3.1 ppb/ppm were assigned as suspicious and NO_x/CO_2 emissions greater than 3.1 ppb/ppm were predicted to be tampered.

Table 3: NO_x/CO_2 ratios (ppb/ppm) used as emission thresholds for SCR tampering of light duty and heavy duty vehicles measured using the ICAD plume chase instrumentation.

Vehicle type	Normal (ppb/ppm)	Suspicious (ppb/ppm)	Tampered (ppb/ppm)
LDV	<1.3	1.3–2.0	>2
HDV	<1.7	1.7–3.1	>3.1

The SCR predictions made using the PS and RS measurements were based on whether the NO_x/CO_2 ratios exceeded the Euro 4 emission standards. Table 4 shows the NO_x emission standards for each test vehicle and the corresponding NO_x/CO_2 ratios. For the N1 vehicles, the CO_2 emissions were assumed to be 140 $g\,km^{-1}$. For the truck, the motor efficiency was assumed to be 0.4 and the CO_2 emissions per litre of diesel burnt were 2.64 $kg\,L^{-1}$. Vehicle SCR systems were considered tampered if the NO_x/CO_2 ratios were above or approximately equal to the stated thresholds.

Table 4: Euro 4 NO_x emission standards and the corresponding NO_x/CO_2 ratios used as point sampling and remote sensing SCR tampering thresholds for the Caddy, Transporter and truck.

Vehicle	Vehicle category	Euro 4 NO_x limit	NO_x/CO_2 (ppb/ppm)
Caddy	N1, class 1	0.25 $g\,km^{-1}$	1.71
Transporter	N1, class 2	0.33 $g\,km^{-1}$	2.25
Truck	N3	3.5 $g\,kWh^{-1}$	5.06

3 Results and discussion

3.1 Detection of SCR system tampering

3.1.1 VW Caddy

This section will focus on the extent to which NO_x/CO_2 ratios measured using the different remote emission sensing techniques can be used to predict whether a vehicle's SCR system is operating. Figure 1 shows the NO_x/CO_2 ratios obtained from valid Caddy PC, PS and RS measurements. Each session consisted of multiple plume chases or vehicle passes. The PC data points show an average ratio for a single vehicle chase and the PS and RS data points show a single measured ratio for a vehicle pass. The shape of the data points corresponds to whether the SCR system was predicted to be tampered, operating normally, or unknown.

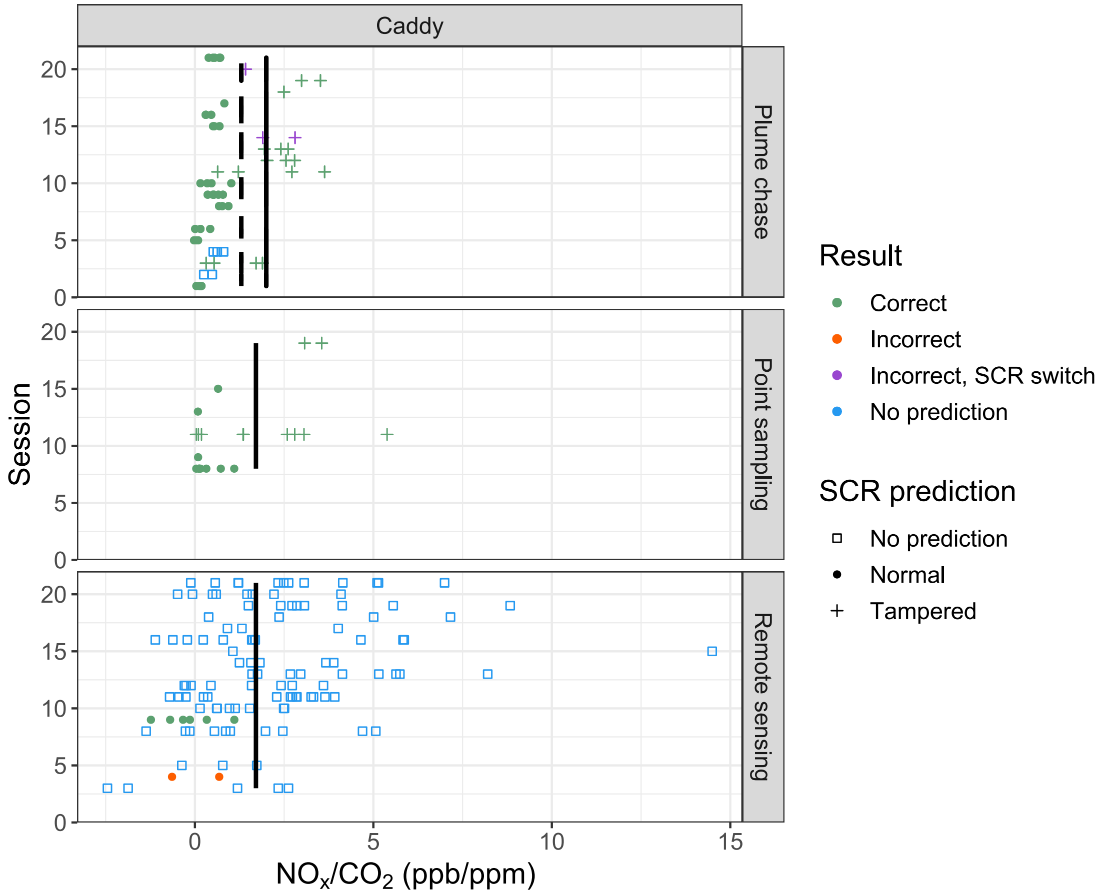

Figure 1: NO_x/CO_2 ratios (ppb/ppm) for the Caddy, measured by plume chase, point sampling and remote sensing techniques, grouped by test session. The data point shape corresponds to the predicted state of the SCR system and the data points are coloured according to whether the prediction was correct. The vertical dashed and solid lines show the 'suspicious' and 'tampered' emission thresholds.

The colour of the data points indicates whether the predictions were correct (green) or incorrect (orange). The blue data points show sessions for which it was not possible to predict the state of the SCR system.

During the characterisation experiments, some of the tampering predictions were incorrect for the measurements conducted shortly after a switch between SCR on and off, or vice versa. This is likely a result of residual NH_3 available for the reduction of NO_x after the SCR system is switched off, or due to the time taken for the SCR system to warm up when it is switched on (producing a similar effect on emissions as cold starts). Instances where the prediction was incorrect, but could be attributed to a recent change in the state of the SCR system, are shown by the purple data points. These observations are due to the experimental design and are unlikely to be encountered under real world driving conditions.

The plume chase measurements were highly successful at predicting the correct state of the SCR system for the Caddy. With the exception of sessions 2 and 4, a prediction was made for all test sessions. The results from session 2 were considered ambiguous as the NO_x/CO_2 ratios were rising throughout the session; this may be attributed to the fact that the SCR system was switched off between sessions 1 and 2, and the emissions did not increase until the residual diesel exhaust fluid was used. Although the SCR system was incorrectly predicted to be tampered during sessions 14 and 20, the SCR system had been switched on just before these sessions, and therefore may not have reached optimum operating temperatures at the time of measurement.

Sessions 3 and 4 were carried out under the same constant speed conditions and the SCR system in the Caddy was tampered for both sessions. The SCR system was correctly predicted to be switched off for session 3 but a prediction was not made for session 4 as the measured PC emissions were variable. It is possible that the emissions were lower than typically expected from a vehicle with a tampered SCR system due to the constant speed driving conditions, and that the elevated emissions in session 3 were in fact associated with cold start emissions. A similar observation was reported using the RS measurements; the SCR system was incorrectly predicted to be operating normally during session 4.

For the PS measurements, fewer predictions were made than PC due to the lower availability of valid NO_x/CO_2 ratios. Although only 6 predictions were made, they all correctly identified the state of the SCR system. The SCR system was correctly identified as tampered during session 11, but the individual NO_x/CO_2 ratios ranged from 0.1 to 5.4 ppb/ppm for this session and spanned the tampered emission threshold. The NO_x/CO_2 ratios increased with subsequent vehicle passes during session 11 and this observation can be attributed to switching off the SCR system shortly before session 11 started.

As shown in Figure 1, a higher number of measurements were assigned as valid for RS compared to PS, but the range in NO_x/CO_2 emission ratios for each session was considerably greater. It was only sensible to predict SCR system tampering when measured ratios for a particular session were either all above or all below the emission tampering threshold. Predictions were made for session 4 and session 9; the incorrect prediction associated with session 4 could be due to low emissions associated with constant speed driving conditions, as previously discussed. The SCR system was correctly predicted to be operating normally during session 9.

3.1.2 VW Transporter

Figure 2 shows the measured NO_x/CO_2 ratios for the Transporter, reported by PC, PS and RS. As shown for Figure 1, the shape of the data points corresponds to the predicted state of the SCR system and the colour indicates whether the prediction was correct.

Similar to the Caddy, the highest number of after-treatment tampering predictions for the Transporter were made using the PC measurements. There were two incorrect predictions for sessions 13 and 19. NO_x/CO_2 ratios were likely elevated for session 19 due to cold start emissions, an effect which will be discussed in more detail in section 3.1.3. The SCR system was correctly predicted to be switched on during session 12 and incorrectly predicted to be switched off for session 13. The driving conditions were the same for session 12 and 13; the Transporter accelerated from standstill past the PS/RS equipment and continued around

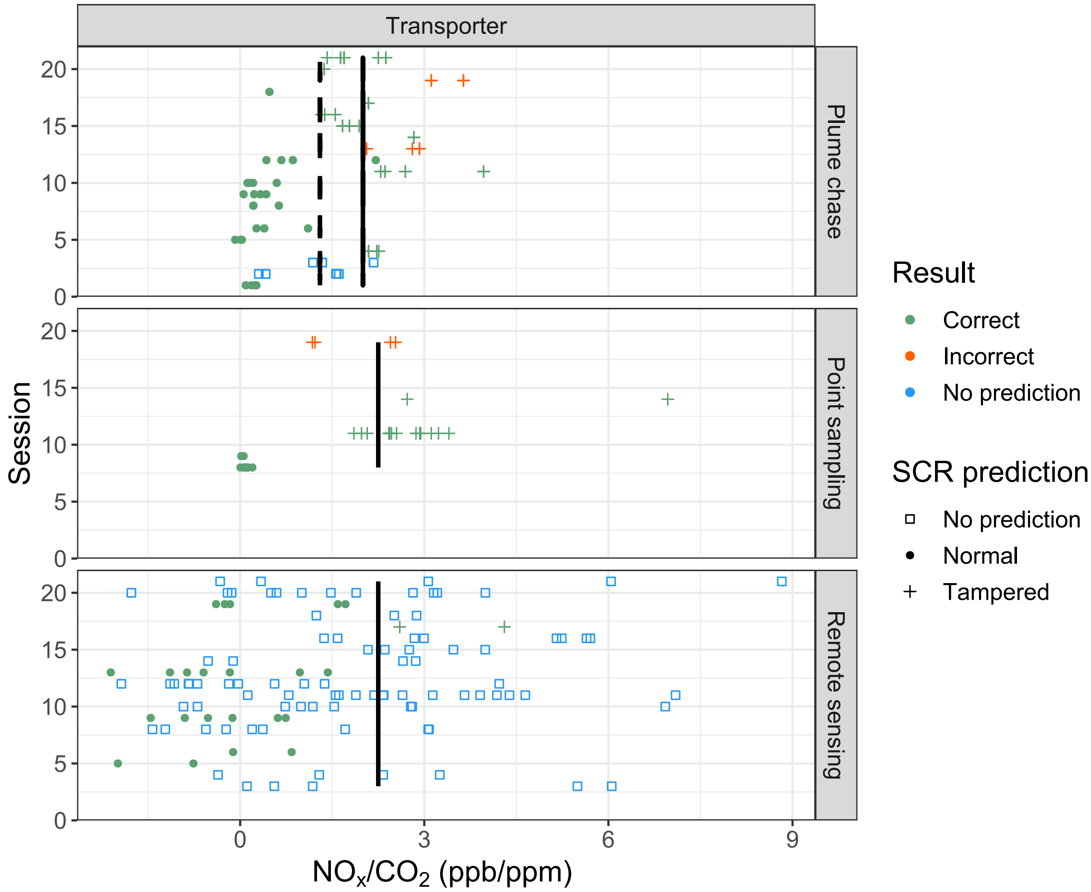

Figure 2: NO_x/CO_2 ratios (ppb/ppm) for the Transporter, measured by plume chase, point sampling and remote sensing techniques, grouped by test session. The data point shape corresponds to the predicted state of the SCR system and the data points are coloured according to whether the prediction was correct. The vertical dashed and solid lines show the 'suspicious' and 'tampered' emission thresholds.

the main track at 80 $km\,h^{-1}$, in a convoy of test vehicles with a 2 second delay between each vehicle. The only difference was the vehicle order within the convoy. Figure 3 shows NO_x emission time series measured by the PC vehicle for these two sessions. The left panel shows the Transporter emissions when it followed the Caddy (session 12) and the right panel shows the Transporter emissions when it followed the truck (session 13). The data shows that for session 13, the NO_x emissions from the truck were high enough to interfere with the Transporter PC measurement and make the vehicle appear as though it had been tampered.

Some of the sessions were specifically designed in this way to investigate occasions when the emissions from the vehicle of interest may be influenced by emissions from other vehicles in close proximity. This effect is most likely to be observed when the vehicle of interest is following a higher emitting vehicle such as a HDV. It is possible to avoid such situations when choosing which vehicle to chase during real world measurements. Nevertheless, in real world settings there is an increased likelihood of interfering plumes from surrounding vehicles, particularly in heavy traffic conditions, and this is important to consider when planning measurements.

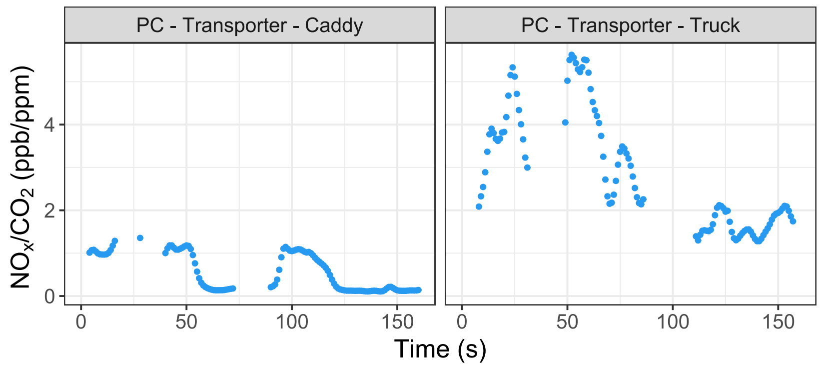

Figure 3: Time series to show the Transporter NO_x/CO_2 ratios measured by the ICAD plume chase instrument. The left panel shows measured emissions when the Transporter is travelling behind the Caddy (session 12), and the right panel shows emissions when the Transporter is travelling behind the truck (session 13).

Fewer predictions were made using PS due to the lower number of valid measurements available. 4 out of the 5 predictions were correct for the Transporter, and session 19 may have been incorrectly predicted due to cold start emissions at the start of the day. For RS, 4 correct predictions were made, when all individual data points for a particular session were below the emission threshold for tampered vehicles.

3.1.3 Truck

The SCR system fitted in the truck was switched on and off throughout the experiments, and the predictions based on the measured NO_x/CO_2 ratios are shown in Figure 4. For the PC measurements, the only 2 incorrect predictions were associated with recent switching of the state of the SCR system, which is an effect of the experimental design. A greater number of predictions were made by PS (14) and RS (9) compared to the number of predictions made for the Caddy and Transporter, due to the increased difference in NO_x/CO_2 ratios for SCR on versus SCR off. As observed for PC truck measurements, the only incorrect predictions made using PS and RS measurements were associated with SCR system switching between sessions.

There are occasions when the ability to detect vehicle tampering may be affected by measuring emissions from a cold start engine. As shown in Figure 4, the truck SCR system is correctly predicted to be switched on during session 8. However, there are some individual vehicle chases within session 8 for which the NO_x/CO_2 ratio exceed the 'tampered' threshold of 2.5 ppb/ppm. Figure 5 shows NO_x emission time series data for the first and second truck plume chases of session 8. The first plume chase (left panel) was performed at the start of the day when the engine was cold and shows considerably higher NO_x emissions compared to the second plume chase (right panel), when the engine had warmed up. This

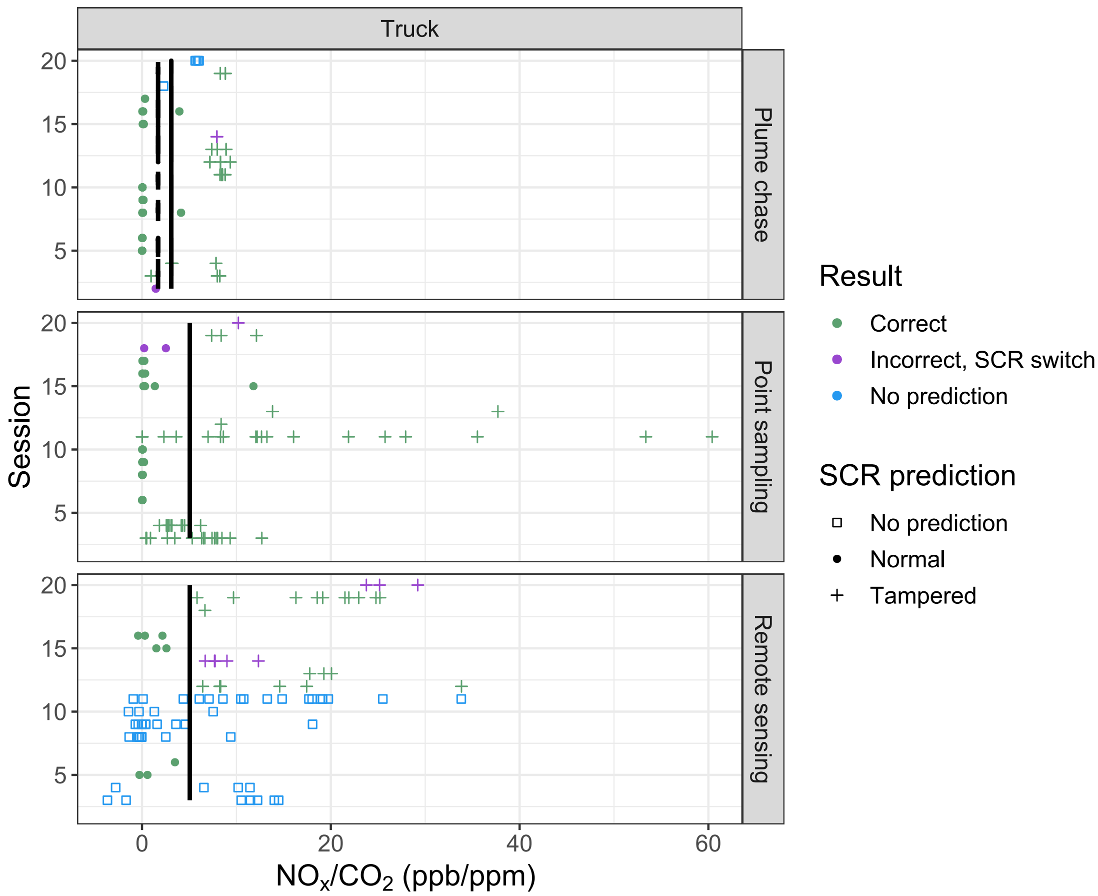

Figure 4: NO_x/CO_2 ratios (ppb/ppm) for the truck, measured by plume chase, point sampling and remote sensing techniques, grouped by test session. The data point shape corresponds to the predicted state of the SCR system and the data points are coloured according to whether the prediction was correct. The vertical dashed and solid lines show the 'suspicious' and 'tampered' emission thresholds.

highlights an important consideration when trying to detect SCR emulators in the real world; the potential for emissions from a cold start engine to be falsely interpreted as a vehicle with a tampered SCR system.

3.1.4 Summary

It was possible to predict the SCR system state for a greater number of sessions using the PC measurements compared to the PS and RS measurements. This is expected because an individual plume chase is typically carried out for several minutes and results in detailed emissions information for a particular vehicle of interest. On the other hand, PS and RS monitor 'snapshot' emissions behaviour for each passing vehicle. Whilst the detailed emissions behaviour obtained by PC measurements is very valuable for predicting after-treatment system tampering, the drawback is that the number of vehicles that can be

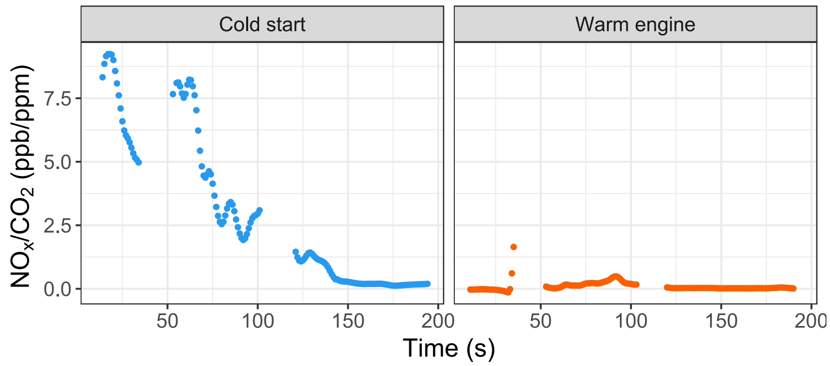

Figure 5: Time series to show the truck NO_x/CO_2 ratios measured by the ICAD plume chase instrument. The blue data points represent emissions from a cold start test session (8a) and the orange data points show emissions measured during a session when the engine was warm (8b).

monitored in a set period of time is limited. RS and PS allow for a greater number of vehicles to be measured, but the information provided for an individual vehicle pass is considerably more limited than PC. Repeat RS and PS measurements are needed to say with a certain degree of confidence that a vehicle is tampered, but individual measurements are still useful for flagging potentially tampered vehicles that are worthy of further investigation, using PC measurements or roadside inspection for example.

Overall, there is normally a specific reason why an after-treatment tampering prediction is incorrect. For example, cold start emissions may be falsely interpreted as SCR system tampering. The benefit of PC compared to PS and RS in this situation is that the reduction in emissions with time can be tracked throughout the duration of the vehicle chase, and false positives can be avoided. Incorrect predictions can also occur when measured emissions are influenced by a high emitting vehicle in front of the vehicle of interest. For PC, it is possible to avoid these situations e.g. by not measuring a vehicle that has a HDV driving in front. For PS and RS, the sequence of passing vehicles and the time delay between vehicles is recorded; this data can be used to identify situations when the measured emissions are potentially influenced by emissions from other vehicles.

3.2 Effect of sample size on PS and RS measurements

An important factor that affects the ability of different techniques to detect vehicle tampering is sample size. Simulations have been conducted to evaluate the effect of sample size on estimated emissions for RS and PS. To calculate the mean and 95% confidence intervals at different sample sizes, chunks of data with different sample sizes were sampled at random, 1000 times per sample size. For example, for a sample size of 10, 10 values were randomly sampled from the data and the mean calculated. This process was repeated 1000 times to provide 1000 estimates of the mean emission and the 95% confidence interval in the mean. The process was repeated for a range of sample sizes as shown in Figure 6.

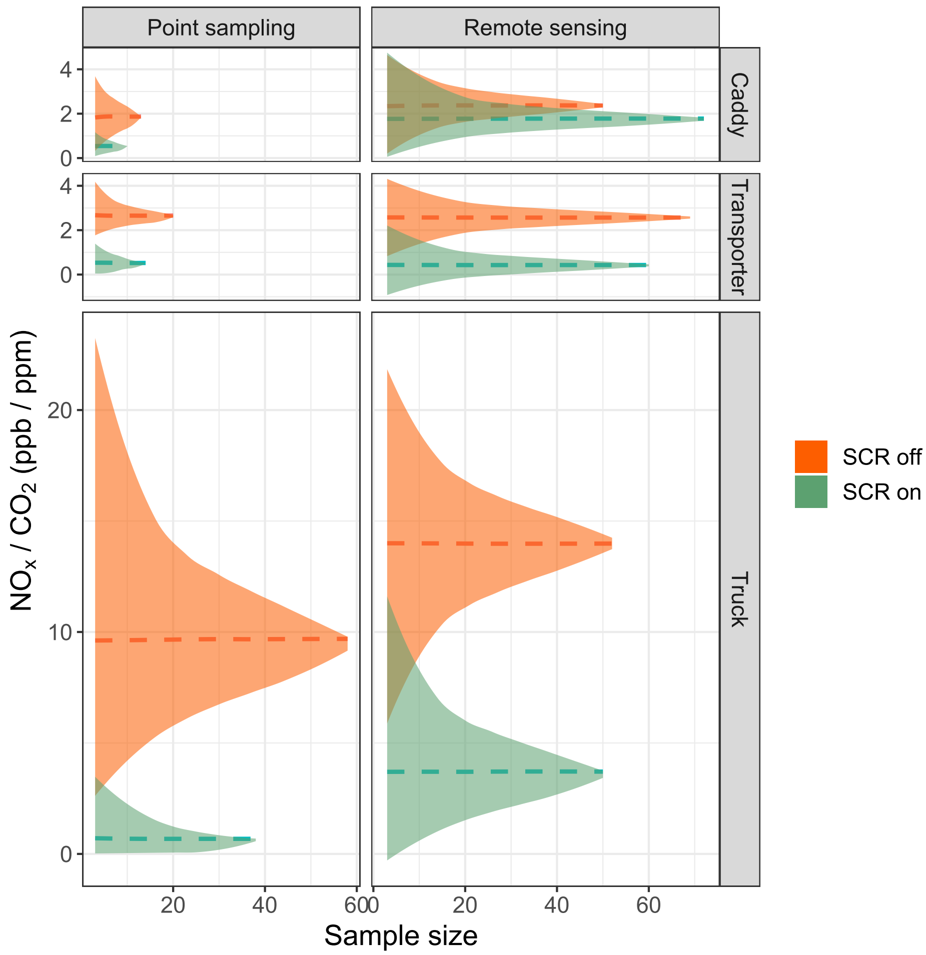

Figure 6: Mean NO_x/CO_2 emission ratios for the Caddy, Transporter and truck, measured by point sampling and remote sensing. The dashed horizontal lines show the average emissions for SCR on (green) and SCR off (orange). The shaded areas show the relationship between the 95% confidence interval in the mean and the point sampling and remote sensing sample sizes, for both SCR on and SCR off.

The dashed lines in Figure 6 show the mean NO_x/CO_2 ratios measured by RS and PS for the Caddy, Transporter and truck, when the SCR system is switched on (green) or off (orange). The shaded areas show the relationship between the 95% confidence intervals in the means and the number of PS and RS measurements for each vehicle and after-treatment state. As expected, for both techniques, the 95% confidence interval in the mean gets narrower as the sample size increases. This demonstrates that as more repeat measurements of the same vehicle are collected, the certainty to which the SCR system can be defined as on or off increases.

The proportion of valid PS measurements collected during the week of characterisation experiments was lower than the proportion of valid RS measurements obtained. However, it is important to consider how the 'information value' of these two sets of measurements compare. Fewer PS measurements assigned as valid are available, but also fewer repeat valid PS measurements are needed to distinguish SCR on or off with a 95% degree of confidence, compared to RS.

For the Caddy, the average NO_x/CO_2 PS ratios are 0.5 and 1.9 for the SCR on and off and the 95% confidence interval in the mean for SCR on and off respectively are separable after approximately 6 repeat measurements. On the other hand, the mean NO_x/CO_2 RS ratios for the Caddy are much closer together (1.8 for SCR on, 2.4 for SCR off), and approximately 47 repeat measurements are needed to separate the upper limit of the 95% confidence interval for SCR on from the lower limit of the 95% confidence interval for SCR off.

The same effect is seen for the Transporter and the truck, except that the NO_x/CO_2 ratios for SCR on and off differ to a greater extent, so overall a lower amount of measurements are needed for both PS and RS to distinguish between SCR on and off compared to the Caddy. For the Transporter, a single PS measurement shows a difference in NO_x/CO_2 ratios for SCR on and off to a 95% degree of confidence, whereas around 11 RS measurements are needed to show this. For the truck, 5 measurements are required for PS compared to 9 measurements for RS.

3.3 Detection of DPF tampering

3.3.1 Point sampling

To assess the ability of the particle analysers to detect DPF tampering, a DPF bypass was installed in the Caddy. Although opening the DPF bypass potentially caused a more subtle increase in particulate emissions than fully removing the DPF, the ability to detect this change using different remote emission sensing techniques was investigated. Table 5 shows the average Caddy PN and BC emission factors for a range of point sampling particle analysers, grouped by vehicle passes with the DPF operating normally (bypass closed) and the DPF tampered (bypass open). In total, there were 77 vehicle passes when the DPF bypass was closed and 163 passes when the bypass was open. The number of valid measurements for each group is shown in Table 5, in addition to the data capture success rate (percentage of valid measurements).

For all PS instruments, the percentage of valid measurements was lower when the DPF bypass was closed compared to when the DPF bypass was open; the percentage of valid measurements ranged from 0 to 1.3% when the DPF was operating normally and from 5.5 to 20.9% when the DPF was tampered. The average valid PN and BC emission factors per session for each instrument were higher when the DPF was tampered compared to the few valid EFs measured when the DPF was operating normally. Although it was challenging to quantify the PN and BC emissions from the Caddy for every vehicle pass due to the low particle emissions, these results provide the first indication that the PS analysers were able to detect a change in emissions when the DPF bypass was opened.

Figure 7 shows the PN emission factors from valid Caddy point sampling measurements obtained using the DC and the EEPS, grouped by test session. The shape of the data points shows whether the DPF was predicted to be tampered, and the colour of the data points shows whether the prediction was correct or no prediction was made. For the DC, the Caddy

Table 5: Mean PN and BC concentrations emitted from the VW Caddy, grouped by particle analyser and the state of the DPF bypass. The number (n) and percentage of valid measurements for each group is provided.

Particle number analysers				
Instrument	**DPF**	**PN (#/kg fuel)**	**n**	**% valid**
DC	On	–	0	0
	Off	1.3×10^{14}	23	14.1
EEPS	On	3.5×10^{14}	1	1.3
	Off	8.9×10^{15}	22	13.5
CPC 1	On	5.0×10^{12}	1	1.3
	Off	6.2×10^{13}	25	15.3
CPC 2	On	–	0	0
	Off	2.0×10^{15}	32	19.6
Black carbon mass analysers				
Instrument	**DPF**	**BC (mg/kg fuel)**	**n**	**% valid**
BCT	On	–	0	0
	Off	29.1	34	20.9
AE33	On	–	0	0
	Off	36.1	9	5.5

DPF was correctly predicted to be tampered when sessions containing multiple PN emission factors above the instrument detection limit were measured, as shown by the green data points in the top panel. For sessions 8–10, the PN measurements obtained using the DC were considered invalid as they were below the instrument detection level. The DPF was correctly predicted to be operating normally for these sessions, purely on the basis that the emissions were too low to quantify. In addition, it is important to note that the DC was not functional during sessions 3-7 and therefore no results are reported for this period.

The EEPS PN measurements were also used to predict DPF tampering, as shown in the bottom panel of Figure 7. In general, a similar approach was adopted whereby the DPF was assumed to be operating normally if the majority of the measured EFs in a session were below the instrument detection limit. For session 9, there was a single PN EF above the limit of detection, as shown by the green circle point on the plot, and the remaining measurements for the session were below the instrument detection levels. Additionally, there was no valid data obtained using the CPC. As a result, the DPF was correctly predicted to be operating normally. This highlights that when particle emissions are low and the difference between emissions for a normally operating and tampered DPF are small, repeat PS measurements are useful to predict the state of the after-treatment system.

The DPF was correctly predicted to be tampered for sessions 3 and 12 based on the EEPS data. However, in both cases the elevated PN measurements within both sessions were

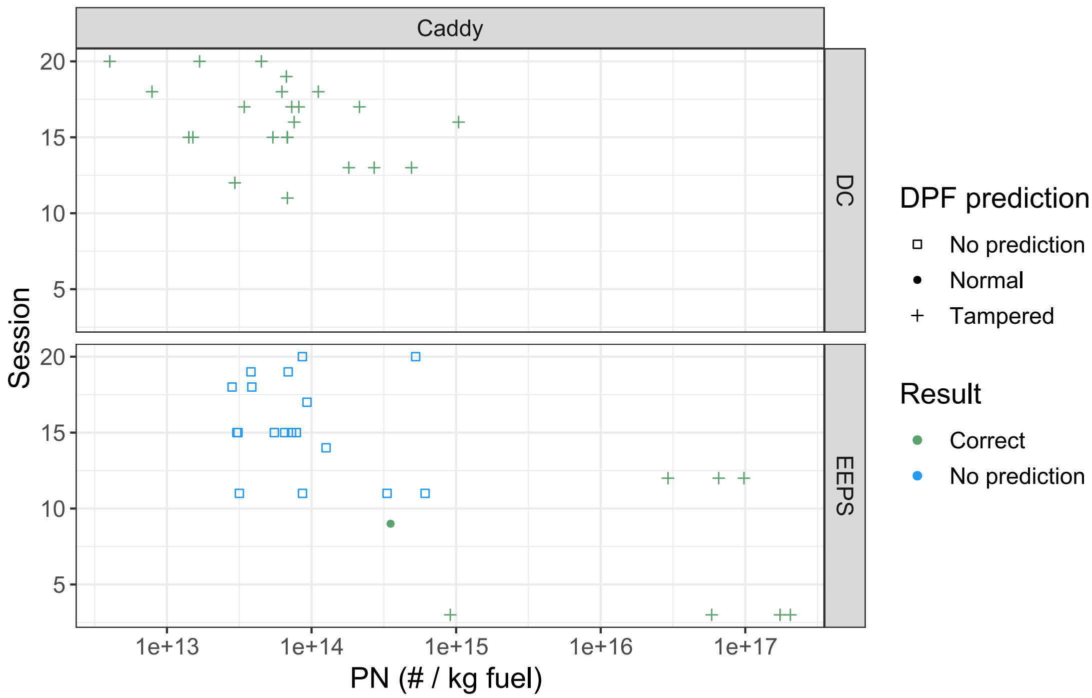

Figure 7: PN emission factors (#/kg fuel) for the Caddy, measured by two point sampling analysers (DC and EEPS), grouped by test session. The data point shape corresponds to the predicted state of the DPF and the data point colour shows whether the prediction was correct.

recorded during a 10 minute period. This increased concentrations may be caused due to a filter regeneration event. For sessions 11, 14–15 and 17–20, a prediction has not been made using the EEPS data. Although there are several measurements above the detection limit, as shown by the blue data points, the instrument operator did not consider the EFs to be high enough to indicate DPF tampering. This observation is attributed to the more subtle effect on particle emissions resulting from opening the DPF bypass compared to if the DPF was malfunctioning completely.

Figure 8 shows the BC emission factors from valid Caddy point sampling measurements obtained using the BCT, grouped by test session. As shown for the PN measurements in Figure 7, the DPF was correctly predicted to be tampered for sessions when BC emissions above the instrument detection limit were reported. Sessions with BC measurements below the instrument detection limit were correctly associated with a DPF operating normally.

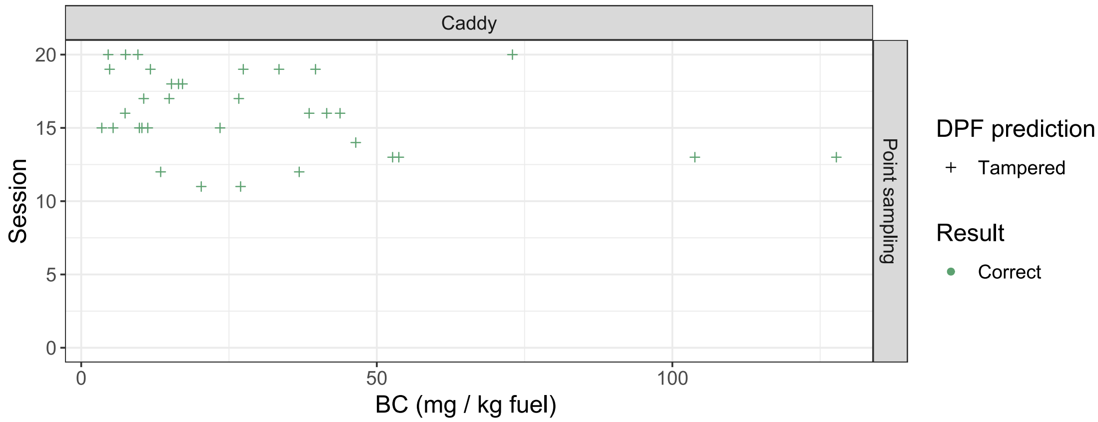

Figure 8: BC emission factors (mg/kg fuel) for the Caddy, measured using the BCT, grouped by test session. The data point shape corresponds to the predicted state of the DPF and the data point colour shows whether the prediction was correct.

3.3.2 Plume chase

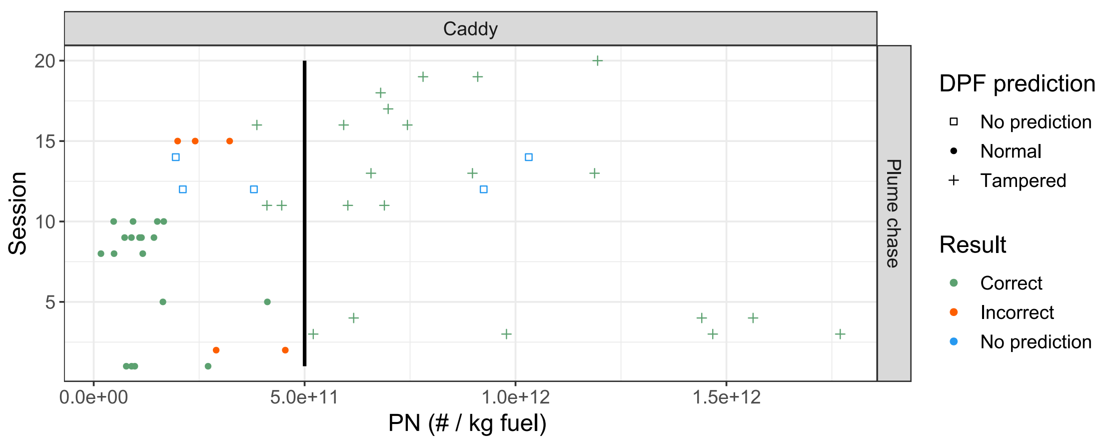

Figure 9: PN emission factors (#/kg fuel) for the Caddy, measured using the SMPS (90 nm) in the PC vehicle, grouped by test session. The data point shape corresponds to the predicted state of the DPF and the data points are coloured according to whether the prediction was correct. The vertical solid line show the DPF tampered emission threshold.

A scanning mobility particle sizer (SMPS) was installed in the PC vehicle and was configured to measure particles around a diameter of 90 nm. The predictions of DPF tampering for the Caddy using the 90 nm PN measurements are shown in Figure 9. The DPF was correctly predicted to be tampered when the measured PN emission factors were above 5×10^{11} particles per kilogram of fuel. Emissions below 5×10^{11} were associated with the DPF operating normally. Using this approach, 5 of the 7 predictions for the DPF operating normally were correct. All of the 9 predictions made for sessions when the DPF was tampered were also correct. PC measurements can provide a detailed insight into after-treatment system tampering as emissions for a particular vehicle are typically monitored over several minutes. However, for some sessions (session 12 and 14) it was not possible to predict whether or not the DPF was tampered as average PN emissions per vehicle chase spanned the emission threshold for DPF tampering and ranged from 1.9×10^{11}–1.0×10^{12} particles per kilogram of fuel. It must be mentioned that the PN emission factors acquired with the SMPS can not be compared in absolute numbers to the reported emission factors of the PN instrumentation (e.g. DC, CPC, EEPS) due to selection of a specific size range of particles (90 nm).

3.3.3 Remote sensing

The Opus remote sensing device measures percentage opacity in the UV channel, which can be used to estimate vehicle particulate emissions. Figure 10 shows the average UV opacity measurements for the Caddy, grouped by test session. The error bars show the 95% confidence interval in the mean and the shape of the data points shows whether or not the DPF was tampered. The results are based on 77 Caddy emission measurements when the DPF was operating normally and 163 measurements when the DPF was tampered. Figure 10 shows that the average UV opacity readings are approximately zero and there is no statistically significant difference between DPF tampered and untampered.

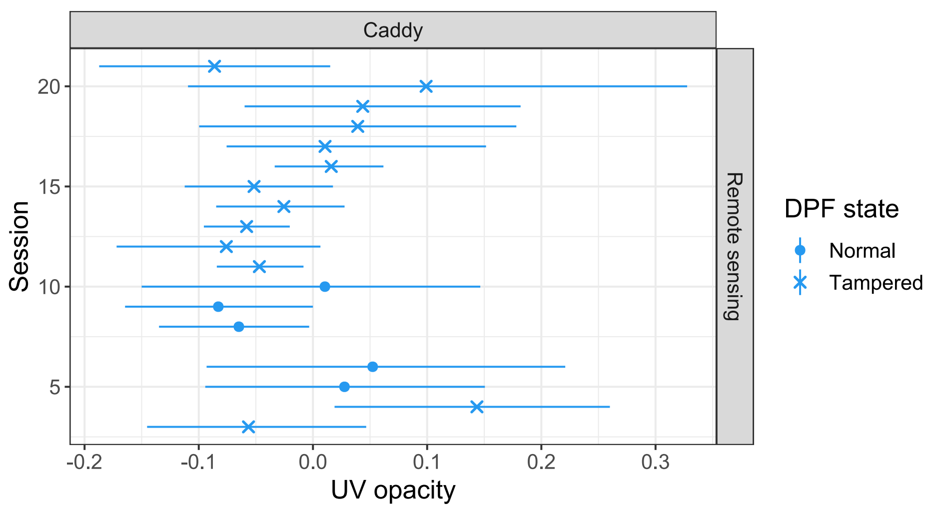

Figure 10: Mean UV opacity measurements for the Caddy, recorded by the Opus remote sensing device. The error bars show the 95% confidence interval in the mean. The shape of the data points shows whether the DPF is operating normally or is tampered.

Unlike PS, it was not possible to predict whether the Caddy DPF bypass was open or closed using the RS UV opacity measurements. However, the increase in particulate emissions resulting from opening the DPF bypass is expected to be more subtle than completely removing the DPF, so in some cases the RS UV opacity channel may provide insight into vehicles with malfunctioning DPFs that are causing very high levels of particulate emissions. Previous studies have highlighted the ability of RS to show population-level differences in vehicles with and without DPFs, and suggest that RS devices can be used as first phase instruments to locate probable DPF malfunction in a vehicle [2, 3]. More research is required to review the extent to which commercial cross-road RS systems are able to identify vehicles with malfunctioning or tampered DPFs.

3.3.4 Summary

The PN and BC emissions from the Caddy were typically below the detection limits of the PS instruments when the DPF was operating normally. When the measured particle emissions were consistently above the instrument detection limits for several vehicle passes within a particular session, the DPF was predicted to be tampered. In general this led to accurate predictions and in the real world, it is likely that many other diesel vehicles will have higher levels of particle emissions and the difference in emissions between DPF on and DPF tampered will be more easily detected.

The plume chase PN measurements performed using the SMPS (90 nm) were also used to predict DPF tampering, and as found for the SCR system tampering, measuring a single vehicle over several minutes gives an accurate prediction of after-treatment system tampering. Due to the strengths and weaknesses associated with the PC and PS approaches, it would be valuable to test the particle analysers used for PS in the PC vehicle, and vice versa. Although the UV opacity measurement obtained by RS did not show a statistically significant difference between DPF on and DPF tampered, it may still be a useful way to flag higher emitting vehicles with malfunctioning DPFs that need to be inspected.

Overall, accurate, fast response PN and BC analysers used for PS and PC measurements can be employed for detecting DPF tampering and quantifying the emissions. Testing a wider range of vehicles to establish appropriate emission thresholds for DPF tampering would be important. Repeated measurements would allow a more certain assumption of the tampering state to detect DPF tampering with a 95% degree of confidence.

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