SEMS Operating as a Proven System for Screening Real-World NO_x and NH_3 Emissions

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Summary

NO_x emissions of heavy-duty and light-duty diesel vehicles depend strongly on the driving conditions. The introduction of combined emission reduction technologies in Euro VI vehicles have demonstrated that NO_x emissions become less predictable when the data is based on relatively short test cycles. Due to the decreased predictability with the increased complexity of the after-treatment technology, emission measurement over longer periods of testing time is required.

Commissioned by the Dutch Ministry of Infrastructure and the Environment, TNO recently started the development of a simple, robust and low-cost emission screening tool called SEMS (Smart Emission Measurement System). The system is able to perform NO_x and NH_3, or ammonia, emission measurements as a stand-alone system for periods of over a week.

The system was tested on two Euro-VI trucks; a city distribution truck and city garbage collection truck. The measurements point out specific NO_x and NH_3 emission behavior which could only be noticed due to the relative long measurement time. With SEMS measurements it is relatively easy to compare the emission results with the results from other measurements whether these measurements were performed by either SEMS or PEMS.

Further equipment developments to improve the systems' accuracy is pointed out. Future perspectives for SEMS are broad and opportunities arise to screen the real-world emissions of for example ships, trains and mobile machinery. The results have led to new insights into real-world NO_x and ammonia emissions of heavy-duty diesel trucks that show that SEMS is proven system to screen the real-world NO_x emissions.

Background

Commissioned by the Dutch Ministry of Infrastructure and the Environment, TNO regularly performs measurements to determine the in-use emission performance of vehicles in the Netherlands. The main goal of the measurement programme is to gain insight into real-world emissions of heavy-duty vehicles under conditions relevant for the Netherlands.

The NO_x emissions of heavy-duty and light-duty diesel vehicles have shown to vary from vehicle to vehicle and to depend strongly on the driving conditions. Focusing on heavy-duty vehicles, the introduction of Euro VI technology significantly reduced NO_x emissions in most cases and under most relevant conditions. However, the introduction of combined emission reduction technologies in Euro VI vehicles have demonstrated that NO_x emissions become less predictable when the data is based on relatively short test cycles. Furthermore, technology-based emission modelling becomes almost impossible.

To fulfil the European air quality requirements, in particular those with respect to local NO_2 concentration limits, the Netherlands needs robust emission models that enable national and local governments to develop effective measures to improve the air quality. In addition, the effectiveness of evolving EU emission legislation needs to be monitored, which requires a comprehensive and reliable database of real-world NO_x emission measurements. Lastly, vehicles that arrive on the market and fulfil the latest emission legislation stage need to be screened.

Due to the decreased predictability, emission measurement data is required over longer periods of testing time. This would enable vehicle emission modelling to become more robust. Because increasing test time with the regular emission test equipment (PEMS) would lead to unacceptable increase in costs, TNO recently started the development of a simple, robust and low-cost emission screening tool called SEMS (Smart Emission Measurement System). This paper describes the experience gained with SEMS, operating in a stand-alone fashion for a test period of more than 10 days on two Euro VI trucks; a city distribution truck and city garbage collection truck. Both trucks were equipped with an SCR after-treatment system with urea injection.

Development of a new emission screening tool: SEMS

The emission screening tool, in its most simple form, uses an automotive NO_x–oxygen sensor and a GPS. With it, on-road measurements under representative driving conditions have been performed on heavy-duty diesel vehicles. The concentrations measured with SEMS can be linked to tailpipe emissions. The system proved to correlate well with PEMS for Euro-V heavy duty vehicles (Vermeulen, et al, 2012).

New to SEMS is that the system is extended with an automotive ammonia sensor. There are two reasons for this extension. First, the ammonia emissions cross-correlate with the NO_x sensor such that it is impossible to distinguish NO_x emissions from ammonia, or NH_3, emissions. With the ammonia sensor it is possible to distinct NH_3 from NO_x. Second, ammonia itself is a regulated pollutant. With the sensor this pollutant can be measured and monitored under real-world driving conditions. This paper presents the experience gained from the extension with an ammonia sensor.

Preliminary experiments with SEMS

TNO performed several real-world emission measurements with SEMS in the last year. The measurements were performed on a Euro VI city distribution truck and Euro VI city garbage collection truck. Both vehicles are important concerning urban air quality as their normal operating environment is a city. Data was gathered during the vehicles' normal driving and operation conditions for more than one week. SEMS was installed on a distribution truck and garbage collection truck for 10 days. During this period a total of 20 hours of emission data was gathered for the distribution truck and 70 hours for the garbage collection truck. Emission data was only recorded when the ignition key was switched on. Despite both vehicles were given the same time with SEMS installed the total operational time between the two vehicles differs a lot. The garbage truck was operated complete days compared to the couple of hours per day for the distribution truck.

Interesting is the typical vehicle-speed profile of these completely different vehicles which have their own specific mission profile as can be seen in Figure 1. The average vehicle speed of the distribution truck is 25 km/h. Most of the time the vehicle is idling (26%), followed by the speed bins of 20 and 25 km/h (7%), and 85 km/h (7%). It is assumed that the 20 and 25 km/h bins corresponds to urban driving and the 75 and higher bins to extra urban. Commonly, distribution trucks are assumed to have idle operation 15% or less of its time.

With a quarter of the time idling, the contribution of emissions while idling to the total emission is significant, despite the low absolute exhaust gas flow and emission rates.

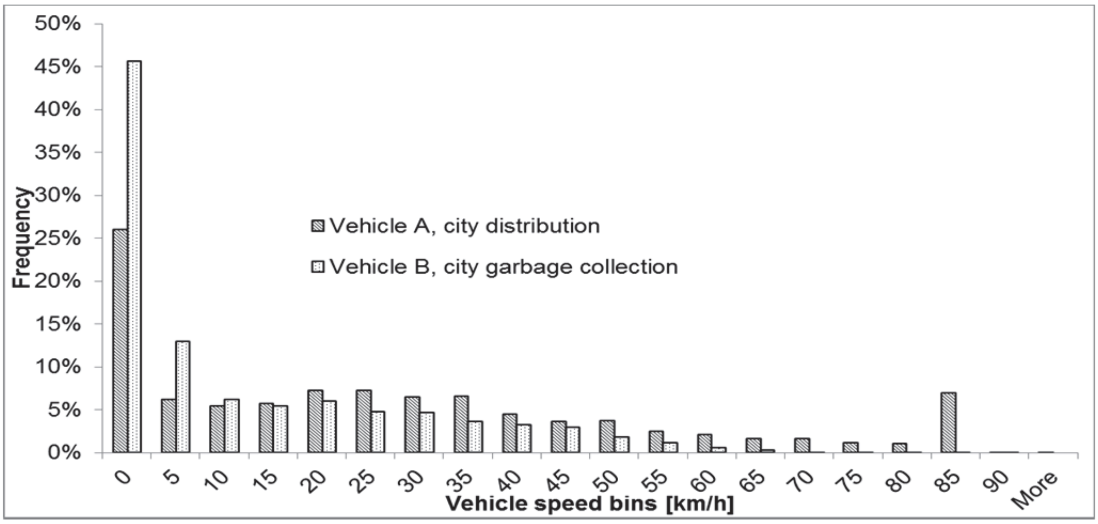

Figure 1: Distribution of vehicle speed over the total operating time of a city distribution and city garbage collection truck.

Euro VI city distribution truck

Figure 2 shows the emission results of the Euro VI distribution truck. It gives a good impression of the data gathered over a longer period of time. The emission results are averaged per 1000 seconds of data to get a better readability and overview of the data.

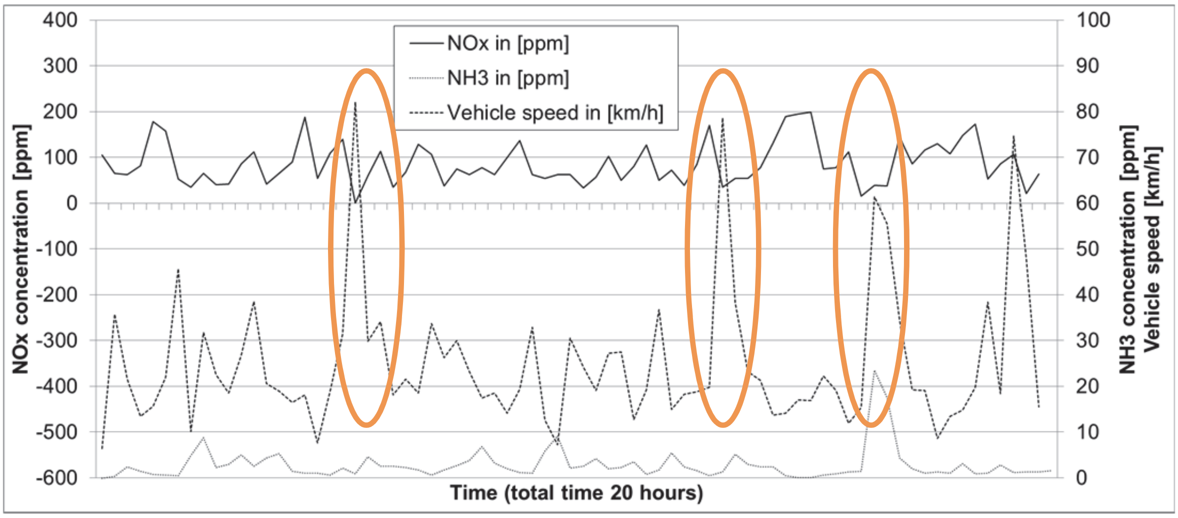

Figure 2: Average NO_x and NH_3 emissions and vehicle speed profile of a city distribution truck. The values are averaged over 1000 seconds of data. In total 20 hours of data is displayed.

The average NO_x emission concentration tops at around 200 ppm, but also very low concentrations of a few ppm are observed. In Figure 2 the circles highlight incidents where low NO_x emissions occur at high vehicle speeds. It seems that the vehicles after-treatment functions better at higher vehicle speeds. This is likely to be caused by the fact that at higher speeds the engine load is higher, which results in higher exhaust gas temperatures. Higher exhaust temperatures result in higher efficiency of NO_x conversion in the SCR system.

At 3 ppm, the total average ammonia emission concentration of the distribution truck is relatively low compared to the Euro VI average ammonia limit of 10 ppm on an emission test bench. For in-service conformity there is no emission limit for ammonia. In the most right circle a high peak (23 ppm) of ammonia emissions is highlighted. Note that the emissions are averaged and the actual ammonia concentrations are momentarily higher. This peak represents roughly one hour of data, which supports the need for longer emission monitoring to get an idea of the real-world emissions of a vehicle.

Euro VI City garbage collection truck

The city garbage collection truck mission profile mainly consists of stop-and-go driving with low vehicle speeds. For this type of vehicle high vehicle speeds are not expected, which is supported by the average vehicle speed of 11 km/h. In Figure 1 the distribution of vehicle speed over the total operating time of the truck is shown. The garbage collection truck has an expected long idle time (46%), followed by most data in the speed bins of 5 km/h (13%) and speed bins of 10 and 20 km/h (both 6%).

The emissions that have been monitored for the distribution truck are depicted in Figure 3. The emission results are averaged per 1000 seconds of data to get a better readability and overview of the data. In total 70 hours of operation were recorded by SEMS.

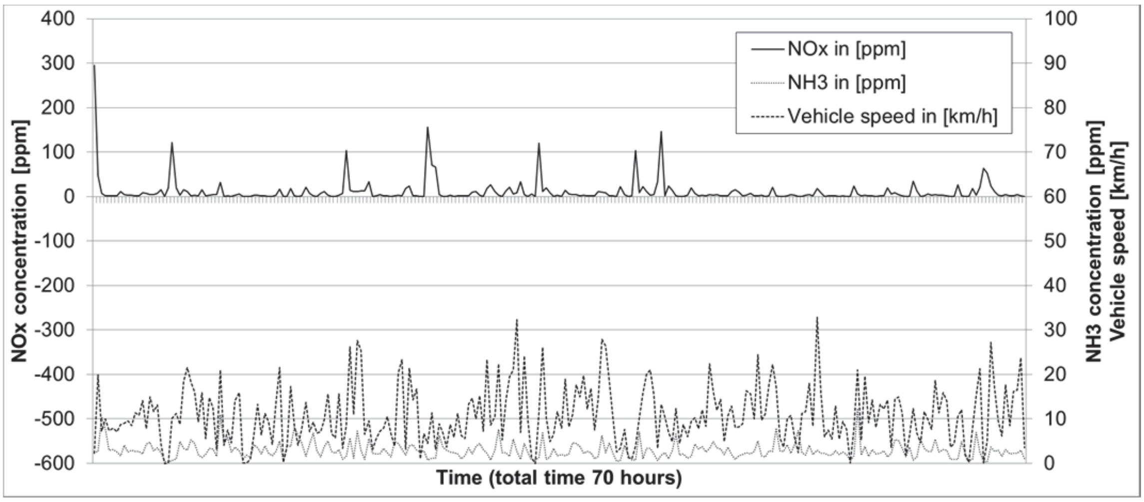

Figure 3: Average NO_x and NH_3 emissions and speed profile of a city garbage collection truck. The values are averaged over 1000 seconds of data. The plot presents 70 hours of data.

In Figure 3 low NO_x emission are observed during the operational time with some peaks above 100 ppm. The average NO_x emission concentration over the total operation time is 10 ppm, which is very low compared to the 86 ppm of average NO_x emissions for the distribution truck. The low NO_x emissions at low speeds are in contrast with the low emissions at high vehicle speeds for the distribution truck. The low emissions may be a logical consequence of the fact that the engine load of the garbage truck is relative high due to usage of a Power take-off (PTO). The PTO is needed to operate the compression unit in the truck to compress the collected garbage. The high engine load at low speeds could resulted in higher exhaust gas temperatures and resulting in better efficiency of the SCR system in reducing NO_x emissions.

No significant ammonia emissions were observed from the measurements. The maximum 1000-second averaged ammonia concentration is 12 ppm. The total average ammonia emission of 3 ppm is relatively low and comparable with that of the distribution truck. Compared to the distribution truck, the ammonia emissions are more stable with less high peaks.

To fully highlight the capabilities of SEMS, the emission results are processed and compared with other vehicle emission data to be able to evaluate the emission performance of both vehicles. The results are depicted in Figure 4. The large speed bins represent the average CO_2-weighed emissions in urban, rural, and motorway conditions. As can be seen, the Euro VI trucks screened with SEMS show significantly lower NO_x emissions than Euro V vehicles. The two trucks that were subject to SEMS testing show very different emission behavior however, which again indicates that Euro VI vehicles do not show consequent or steady emission performance while operating in an urban environment. Figure 4 is a simplified version of the graph in (Vermeulen, 2014), which more specifically discusses NO_x emissions of Euro VI vehicles under in urban operation and also includes PEMS tests of two Euro VI city buses. The two city buses show the same trends as seen with the SEMS-tested trucks of this paper.

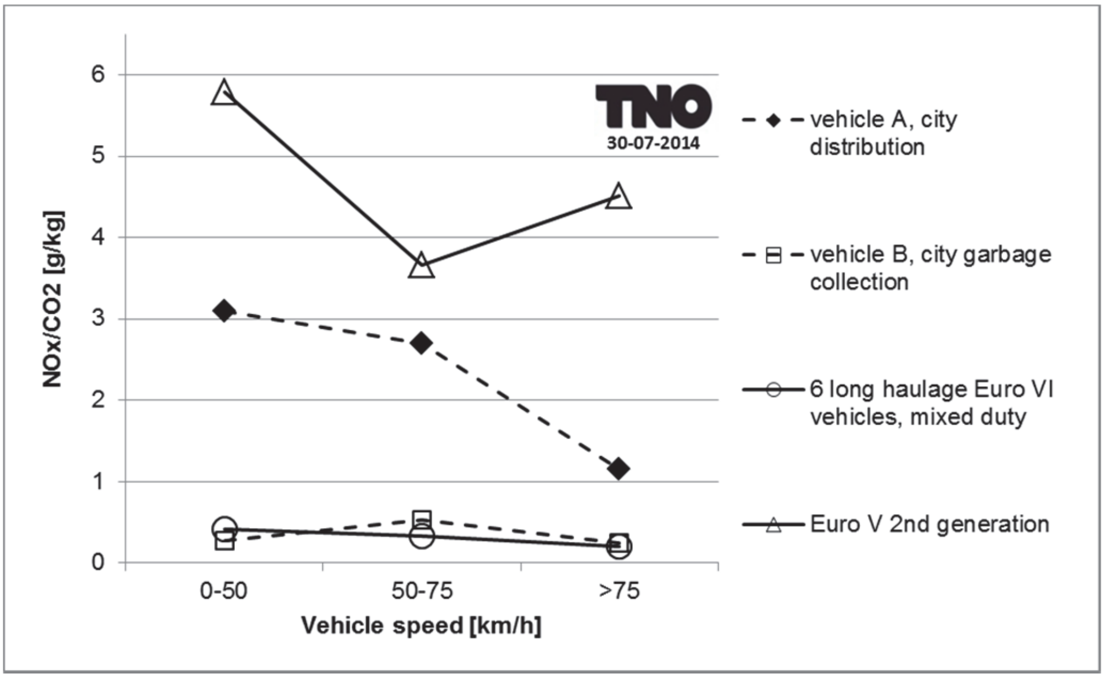

Figure 4: NO_x emission results from SEMS of a city distribution and city garbage collection truck. For comparison the average emissions of 9 Euro V 2nd generation trucks and the average of 6 Euro VI long haulage trucks are added.

Equipment developments

During the last year of performing SEMS measurements on different vehicles the SEMS equipment was further developed. There were four main focus points:

1) To what extent is the ammonia concentration influencing the NO_x sensor reading?
2) To what extent is the pressure difference over the sensor influencing the NO_x sensor reading?
3) What are the limitations if SEMS is operated as a stand-alone unit?
4) What is the future perspective of SEMS?

To answer the first question, SEMS was expanded with an automotive ammonia sensor and subsequently has been installed on several vehicles parallel to reliable NO_x measurements by PEMS. From one vehicle a high peak of ammonia emissions was observed which is depicted in Figure 5. From that figure a clear offset of the NO_x sensor dependent of the ammonia concentration is observed.

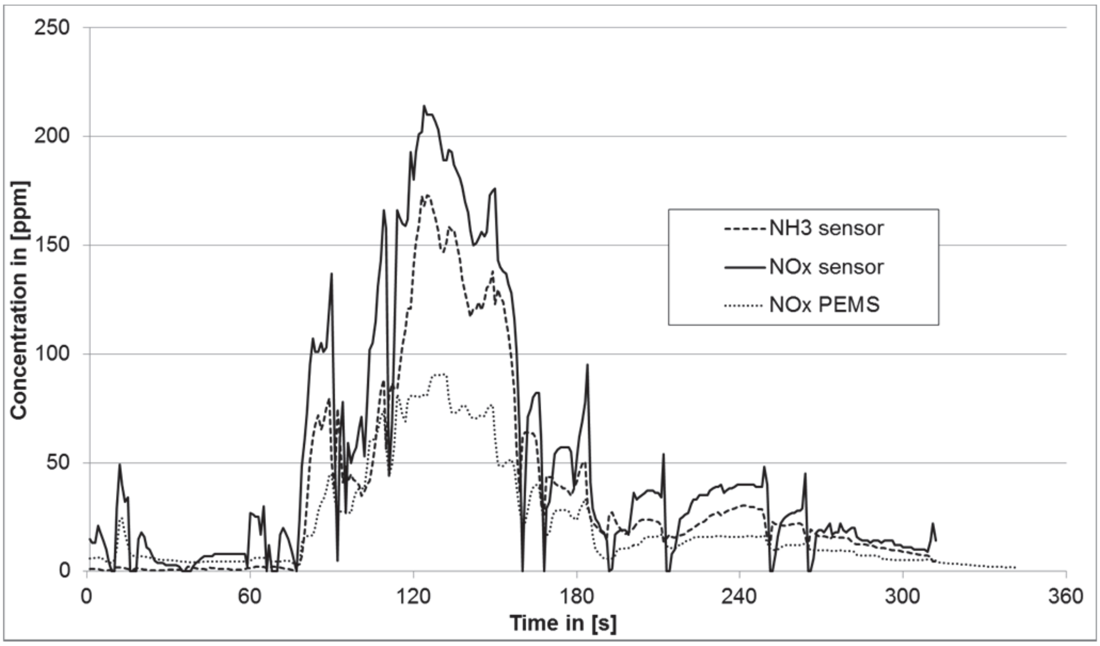

Figure 5: Example of the influence of ammonia concentration on the NOx sensor reading. The PEMS NOx concentration is held as the actual concentration of NOx

A closer look on the cross-dependency of the NO_x sensor from ammonia is gained from Figure 6. In this figure the difference between the NO_x sensor and NO_x concentration measured by PEMS is set out against the ammonia concentration. From the data can be concluded that the NO_x sensor senses ammonia as NO_x by average factor of 0.74, which is significant. This means that if ammonia is sensed, the 'real' NO_x concentration can be calculated by extracting the ammonia concentration, from a separate sensor, multiplied by 0.74.

Once the ammonia influence on the NO_x sensor is taken into account, the average NO_x concentration will be lowered. In the case of the average 3 ppm ammonia observed during the SEMS tests the average NO_x concentration may be lowered by 2 ppm.

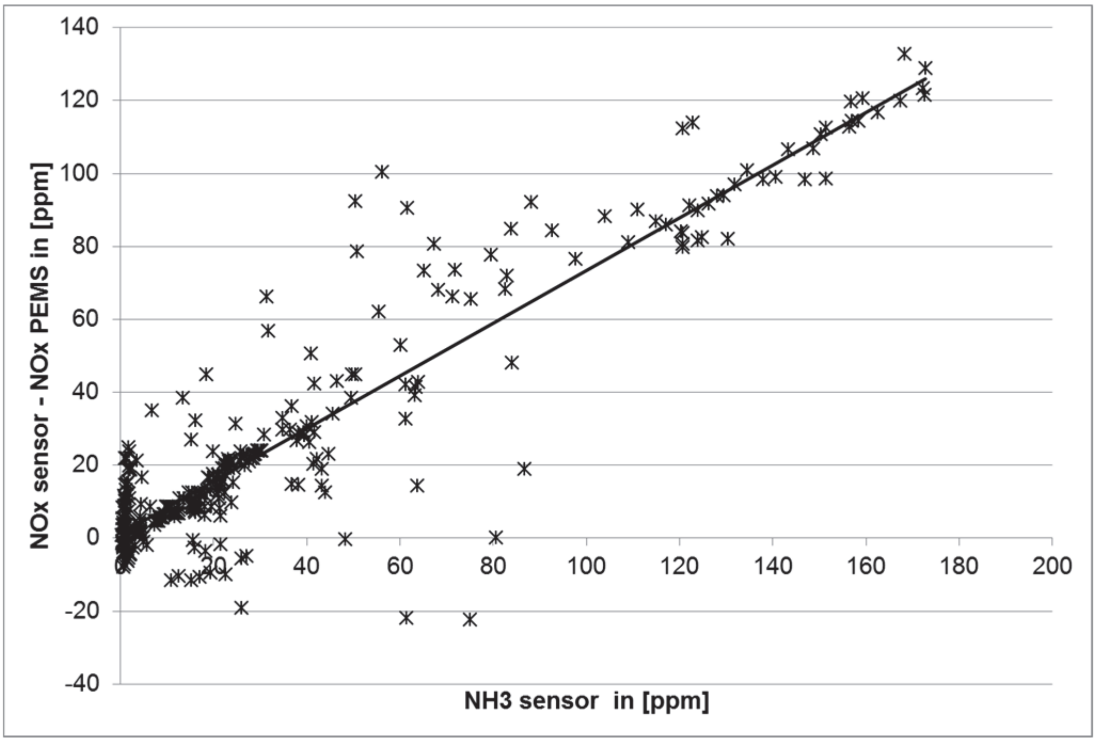

Figure 6: Deviation between the NOx concentration measured by the automotive sensor and that measured by PEMS is set out against the ammonia concentration

The effect of the pressure influencing the NO_x sensor reading can be substantial, although the pressure variation is small in many cases. The pressure influence can be divided in static and dynamic influence. For the static influence a calibration with different NO_x span gasses was performed. During calibration the pressure was statically varied while the NO_x sensor reading was recorded. From the calibration an approximate increase of 2% NO_x sensor reading per 10 kPa of pressure rise was observed. This seems to suggest the NO_x sensor measures NO_x content rather than NO_x concentration. The exhaust pressure is not measured with SEMS. Recommended for further examination is to explore if the NO_x sensor accuracy can be increased with a pressure correction. This could be realized by adding a pressure sensor to the SEMS system and benchmark it against PEMS measurements.

Concerning the dynamic, or fluctuation, pressure influence there is a strong indication that the NO_x sensor signal is shortly dropped when a pressure change in the exhaust is expected, e.g., during acceleration from a stop, change in constant speed to acceleration or deceleration. The drops in NO_x sensor signal can be observed in Figure 5, while the NO_x concentration of PEMS is rather ‘stable’. Despite the short drops in NO_x concentration, it is expected that the effect this has on the average NO_x emissions calculated from the NO_x sensor is cancelled out compared to the limited share compared to the remaining NO_x sensor readings.

For both the distribution truck and garbage truck SEMS was prepared to automatically start logging data when the ignition key was turned on. This automatic operation has a direct influence in how the emission results must be interpreted. Both the NO_x sensor and the ammonia sensor need to be heated before a reliable signal is expected. SEMS is powered by the vehicles’ batteries, which means the batteries will be drawn empty if the sensors are heated constantly. Therefore heating of the sensors is only started when the ignition is on. Analyzing ‘cold start’ emissions are because of that not possible unless heating of the sensor is switched on before the engine is started. Heating of the sensor will typically take around 2 to 5 minutes.

The future perspective of SEMS is versatile. The system has shown to perform well on heavy-duty diesel vehicles and therefore it is expected to gain similar results on light-duty diesel vehicles. Due to the possibility of extending SEMS with additional OBD parameters more in-depth analyses may be made in the future. Besides the automotive sector the system could also be of use for other types of diesel machines like ships, trains and mobile machinery of which real-world NO_x emissions are becoming more important. Currently SEMS is being tested on ships that are being used on inland waterways. Other future possibilities of SEMS are extension to measure other types of fuels such as dual fuel, natural gas or to measure other pollutants like HC, PM and PN.

Discussion and conclusion

With the SEMS measurements of two different Euro-VI vehicles it is proven that the system is capable of screening the NO_x and NH_3 emissions for a longer period of time. SEMS allows for observing specific and incidental vehicles’ emission behavior that require emission screening for a longer period of time, e.g., days and weeks instead of hours. Furthermore, the SEMS system records the way the vehicle is operated and enables emission monitoring during that normal operation, as the system is minimally invasive. The results have led to new insights into real-world NO_x and ammonia (NH_3) emissions and leaves room for improvement to increase the accuracy and reliability of SEMS.

The measurements prove that SEMS is capable of indicating how two totally different diesel vehicles perform compared to other Euro VI vehicles during real-world driving. Moreover, it gives insight into real-world emissions under a wide range of real driving and operation conditions. Finally, it can be used as a tool for screening vehicle emissions.

Acknowledgments

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