Sensoric, measurement, detection and ventilation control

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During optimisation of jet fan control in the Bømlafjordtunnel in Norway we found it necessary to change the way of thinking, and instrumentation of the tunnel was changed.
The Bømlafjordtunnel is a 7.8 km long sub sea tunnel. Low point at –264m below sea level.
Traffic approximately 2500 vehicles a day. With 8.5% decrease as maximum.
When fan control was based on measurement of CO and NO, the line of sight was often drastically reduced.
Earlier experience gave that measurement of dust or aerosols by line of sight would not work satisfactorily.
To gain the most effective control of jet fans we found it necessary to install 4 aerosol measurement units based on backward scatter.
By using aerosol measurement as main control the bill of electricity was reduced, and line of sight drastically improved.
Same principles are now implemented in other long tunnels. Main reason is the good accuracy also with low concentrations, which enables finer tuning of the ventilation control.
Logging measured values of CO, NO and aerosol in $\mu g/m^2$ has given us the opportunity to do some calculations of correlation between values.
Taking in to consideration that the equipment used for monitoring CO and NO has lower accuracy than preferred we still get a correlation due to repeatability.
It is today not possible to get a high concentration of CO without an alarm on aerosol concentration. Using standard tunnel measuring equipment we found a correlation between NO and aerosol >0.8. With ventilation control based on aerosols we never have high concentrations of CO, and very rarely of NO.
In city streets it has been shown a correlation >0.9 between aerosol and NO_2.(Wåhlin and Palmengren 1999).

1) Background

The Bømlafjordtunnel opened for traffic around Christmas 2000. Shortly after, drivers started to complain about the air quality in the tunnel. Since the tunnel originally was equipped with a log, witch logged all analogue values once a minute; we could easily take out the log, after receiving complaints. The problem was that none of the CO or NO measurement points showed high values.
Our own maintenance people confirmed that we had a drastically reduced line of sight when complaints were received. Figure 1 shows the position of measuring stations in the tunnel. At this time only CO, NO and flow was installed.
Experience gives that from time to time we will have high humidity and congestion to fog inside a tunnel. But in this tunnel aerosol (soot) was the main suspect. To be able to decide what caused reduce sight we installed a lot of measurement positions of aerosol, humidity and temperature. The complete new measuring program is listed in table 1.

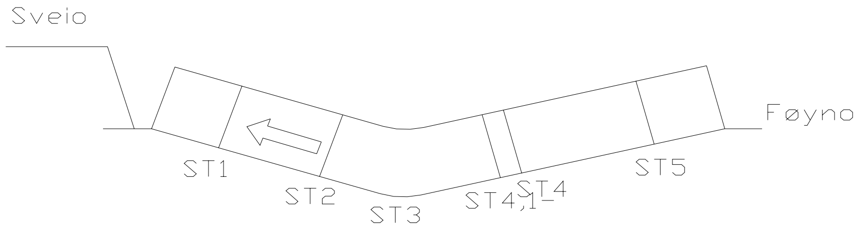


Figure 1

Measuring station	Placed	Euipment
Sveio	30m before the tunnel	Temperature and humidity
St1	970m from Portal Sveio	Temperature, humidity, CO, NO, Aerosol and flow
St2	2430m from Portal Sveio	Temperature, humidity, CO, NO, and Aerosol.
St3	3600 m from Portal Sveio, low point of tunnel	Temperature, humidity, CO, NO, Aerosol and flow
St4,1-	4680 m from Portal Sveio	Aerosol
St4	4980m from Portal Sveio	Temperature, humidity, CO, and NO
St5	6850m from Portal Sveio	Temperature, humidity, CO, NO, and Aerosol.
Føyno	130 m after portal Føyno	Temperature and humidity

Table 1

2) Measuring techniques

Why bother with aerosol measurement at all, why not just run the vetiltation by CO and NO measurement.

The trouble with this is the accuracy of electrochemical sensors, with respect to measured values.

The typical concentration of CO during drastically reduced line of sight was found to be 20-30ppm. A start criteria for the ventilation based on low concentrations of CO were not recommended, even by producer. The same problem will arise if you try to run the ventilation by NO measurement. Using NO_2 becomes impossible. Electrochemically measured NO_2 will, when you have detector adjusting for change in humidity, have accuracy around 0.45 ppm if calibrated very often. Unfortunately the electrician installing measurement equipment has

now idea of how or what it is used for. He will give a guaranty that it is not necessary to calibrate more than once a year. Then accuracy will be reduced to approximately 3ppm for NO and 0,57ppm for NO_2.
Closing conditions in the middle of a tunnel are 0.75ppm. Using NO measurement as a measurement for NO_2 improves this some, but closing conditions in the middle of the tunnel is 6.75ppm and the accuracy is approximately 2.6ppm (For measuring NO compensation for change in relative humidity improves the result to approximately 2.2ppm)
You are then left with to options. This is Traffic counting and aerosol measurement. Aerpsol measurement by backward scatter has by parallel measurement by gravimetrical scientific equipment been shown to give an accuracy araound 6% of measured valuIe: (Wedberg 2000)
Norway, we do feel that to run ventilation based on traffic counting will give more ventilation than necessary. That gives us measurement of pollution, and in this case measurement of aerosols, as a basis for ventilation control, when the tunnel not has enough CO
When we are measuring aerosols, we do prefer an answer in $\mu g\ m^{-3}$. This must not be confused with extinction or k-value that is mainly used in the rest of Europe. We do have a formal limit for pollution of dust (1.5mg m^{-3}). When we are measuring soot, this is too high. A measured soot concentration on approximately 700-800 $\mu g\ m^{-3}$ will give a drastically reduced line of sight. Experience shows that in a tunnel with a long line of sight (>2km) people will complain already when the levels are around 400 $\mu g\ m^{-3}$.
How to measure aerosol levels of this magnitude with high accuracy.
If you use an instrument based on transmission, the best instruments, when new calibrated will give accuracy around $\Delta k \approx 0.9 * 10^{-3}$ when k-value are measured. This will in a tunnel, converted to $\mu g\ m^{-3}$, be around 300 $\mu g\ m^{-3}$. You will normally wish to avoid complaints by the public. It is then too easy to just start full ventilation manually. In Norway this is expensive due to partially payment by max effect used.
By installing aerosol (dust or soot) measurement based on backward scatter (main importance is scattered light) the accuracy can be drastically improved.
This enables a fine tuning of the fan control, which made it possible to create a steady airflow on an early time, using only a few jet fans. This has been confirmed in other tunnels using aerosol measurement.
The use of scatter light in Norwegian tunnels are increasing due to good experience when used. But still many people of influence remember dust measurement by transmission, and a situation where the produced CO was in high amounts, so that the easy and proper way to control the fans was by CO measurement.
When you consider this way of controlling the ventilation in a tunnel, give a thought to how you control our own ventilation. I know that traffic and time is used a lot. The ventilation is then turned to a position which normally gives what is felt like acceptable air quality. Do you have to adjust manually when un normal conditions arise ?
By using pollution the system will take care of the ventilation for you, also in then special conditions, like extreme truck traffic. In a high traffic tunnel, with one way traffic, it normally is very little need for artificial ventilation. Piston effect will often give 4-5 m s^{-1}. And this will be sufficient in most tunnels. (Fløyfjellstunnel, each tube 35000, nearly now ventilation needed, 4km)
The tunnels, which are expensive to ventilate, are the long two-way traffic tunnels, with high traffic, that we wished were highways instead.
Thus far we have not been speaking about the air velocity in the tunnel.
To keep an acceptable air quality inside a tunnel we do some calculations resulting in a needed air velocity. How to measure this air velocity?
In any road traffic tunnel you will have a highly turbulent airflow. To measure the velocity in one point close to the tunnel wall will not give you the information you need. In fact if you

measure the airflow in a two way traffic tunnel on the tunnel wall on each side, they will temporarily show different directions, even with low traffic. The only way to measure air velocity inside a road traffic tunnel, and have any accuracy at all is by line integration from one side of the tunnel to the other. Even then, to be able to use the result for anything you will have to use a floating middle value for the last 5-10 minutes. Otherwise piston effect from vehicles will disturb the measurement to much.

3) Results

During the process of optimizing the ventilation of the Bømlafjordtunnel we performed logging of all analogue values each minute for several months. At he same time we logged number of jet fans running. Checking this toward time of complaints from the public enabled us to improve the ventilation, without using too much ventilation.

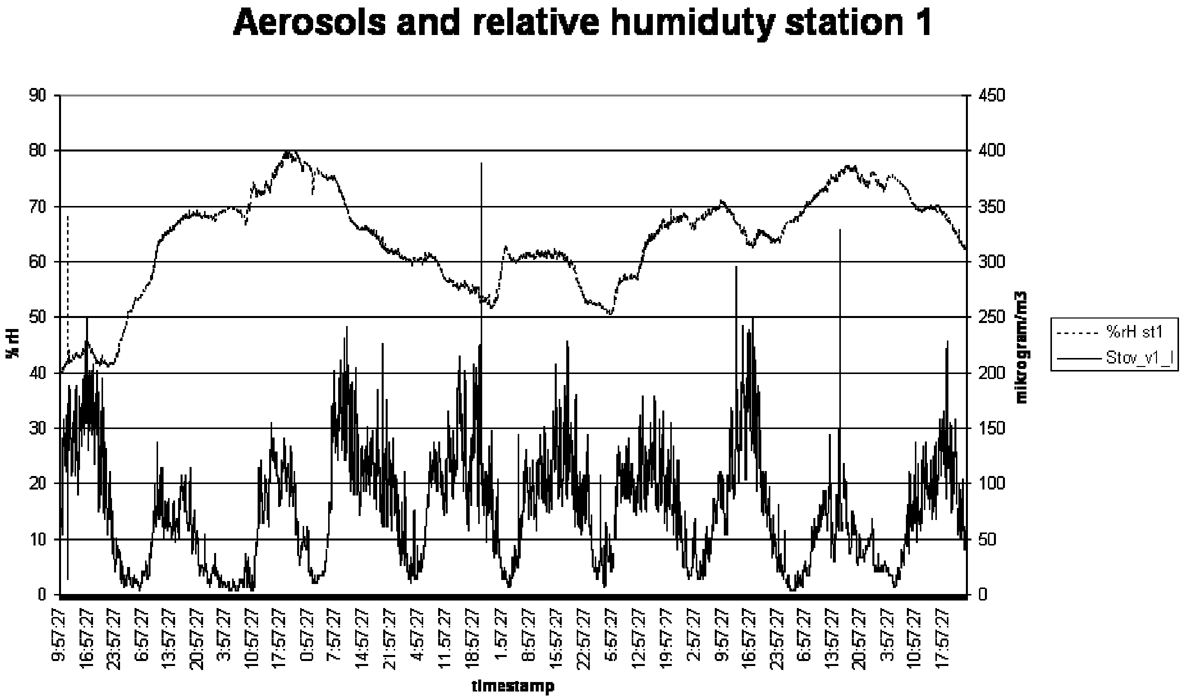


Figure 2

One of the surprising results we can find from this large amounts of data are the surprisingly large variation in rH. And that the measured aerosol concentration in the tunnel normally is completely independent of rH. This is shown in figure 2.

We did also detect abnormal conditions regarding aerosol concentrations. An example of this is shown in Figure 3 for 6 February 2002. The automatic responds to the increased pollution and increase the ventilation. That way it is only a short time with the high concentrations.

The special condition this day was that to have an air velocity in the area of 2-3 m s^{-1} we needed far more power than usual

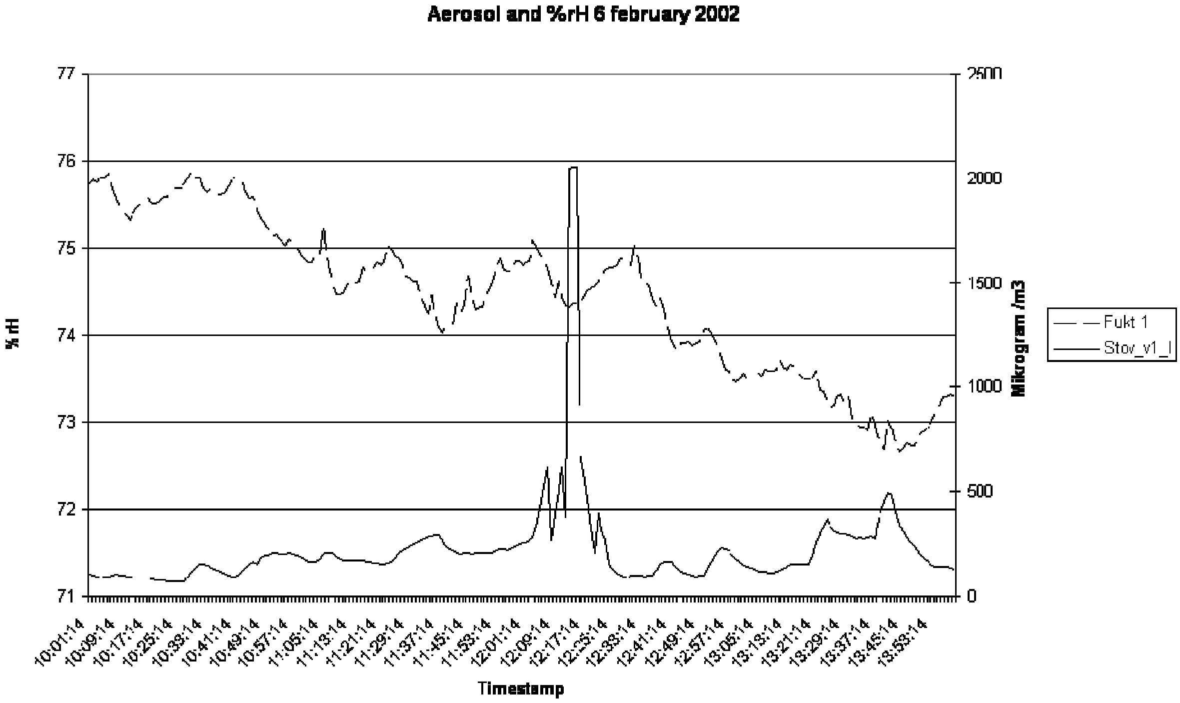
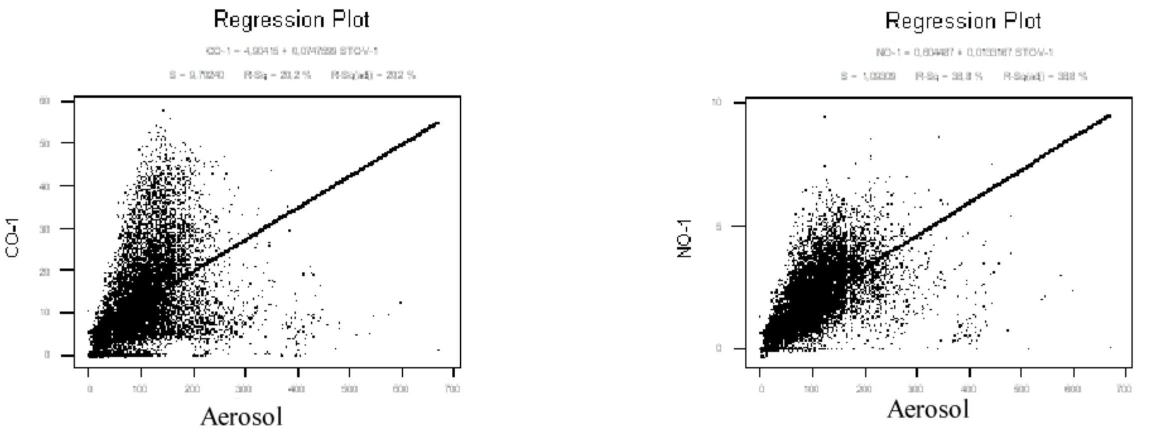


Figure 3

Where we will expect to fin a correlation is between the different compounds in exhaust. Based on the equipment normally used for ventilation control it has been done a thorough analysis of correlations in the Bømlafjordtunnel by (Indrehus Aralt 2003)`), this work shows that CO and NO concentrations not are any problem. This has been confirmed in several investigations (Chan et al. 1996, Kirrchstetter et al. 1999, Kean et al. 2000, ChowChan 2003) Under abnormal conditions they still might be a problem, so it is not recommend to remove them.
From these examinations we can find some correlations that might be useful.
Figure 4 shows regression plot CO/Aerosol and NO / Aerosol



Figur e 4

The actual plots contains data for six weeks. It shows none linearity between CO and aerosols, but it is better when we are comparing NO and aerosols. Calculated correlation is

The reason for removing, or not using NO for ventilation control is shown in figure 5

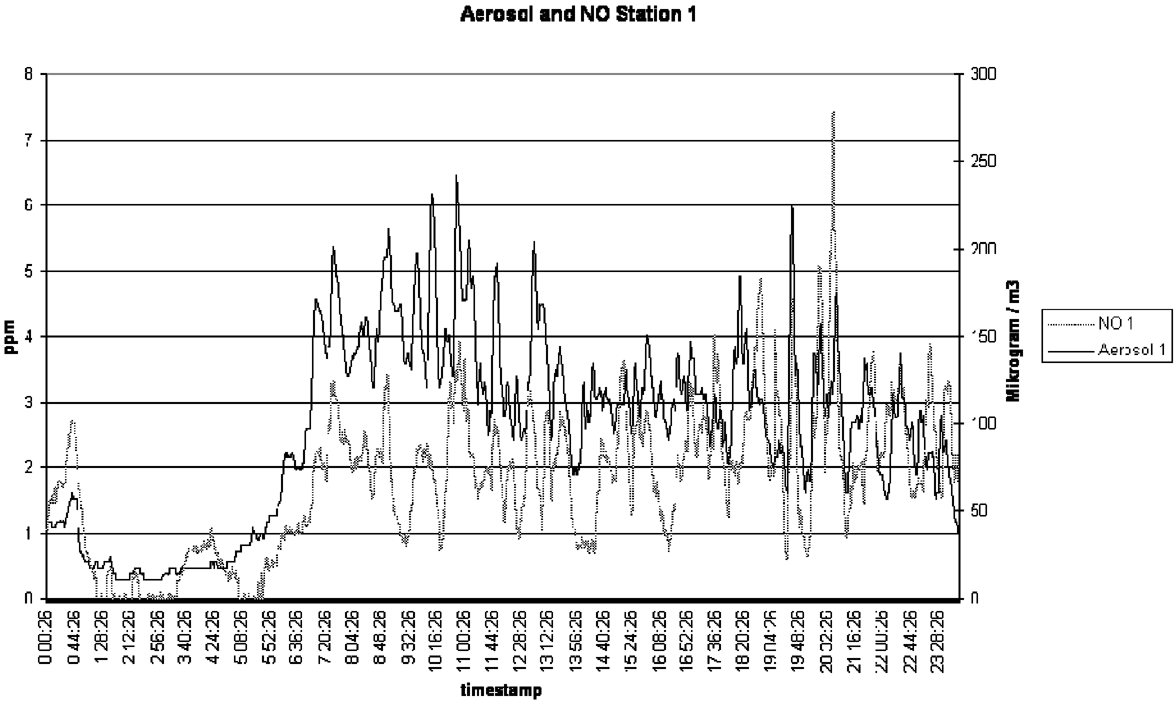


Figure 5 Concentrations near exit of tunnel. Calculated correlation 0.67

A closer inspection reveals that you nearly never have high concentration of NO, without a rise in aerosol. This will be confirmed by any calculation of pollution in a road traffic tunnel. The calculation shows you that it is the production of soot from heavy dusy traffic that will be the dimensional factor for the ventilation due to traffic. (Normally 20MW fire will be dimensional) The production of CO will be so low that it may be neglected unless you have problems wit congestion with very few diesel engines.

Fire

We will here only look on the detectors for ventilation control and how these detector will respond in case of fire. The data used are from a fire drill in the Folgefonn tunnel (11km). The drill was performed by placing an old car 2km inside the tunnel, and igniting it. This was done two times, 1 our between igniting the cars

What happened when the fire-gases reach a measuring station containing CO, NO and aerosol measurement.

Highest measured CO 101 ppm (short time peek)
Highest Measured NO 8 ppm (short time peek)
Highest measured aerosol above limit on 2000 microgram immediately, last for 40 minutes
Wind speed 3m s^{-1}

The fumes could be seen on every measuring station, when it arrived, due to aerosol measurement.
There were no dangerous CO consternations in the tunnel.

Uncertainty's in examination.
Standard industrial measurement equipment used for measuring all values
As shown the accuracy of gas detectors are low for scientific use. Examinations should be done with scientific equipment. Due to outdoor examination we could then expect a better correlation between NO and fine particles.

Appendix A
The approximately accuracy for electrochemical cells are based on
Measuring cells from Dräger,
40% change in relative humidity from calibration point
Variation of air flow 0-6m/s
Variation of temperature from calibration point 10 degrees Kelvin
And other vice as described in datasheet from Dräger

Calculation done by
$d_{Value}=(e1^2 + e2^2 + e3^2 + \ldots + 3n^2)^{0.5}$
Where d_{Value} total error
e1 error number one, e2 error number 2 etc.

Referees

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