UTILISING BAROMETRIC PRESSURE DIFFERENCES TO OPTIMISE TUNNEL VENTILATION SYSTEM DESIGN

Jyh Shim, Daniel Feest, Robert Jones, Mark Gilbey
WSP UK Ltd

ABSTRACT

Long tunnels can be subject to significant barometric pressures across the portals which affects the ability to meet any tunnel ventilation design criteria. The simplest ventilation design outcome can be to provide a ventilation system with enough capacity to implement consistent ventilation modes, regardless of the meteorological pressures; however, this can lead to high airflow capacity requirements. This paper describes an investigation into the feasibility of instead using barometric pressure dependant modes. Three different modes were developed depending on whether the meteorological forces lead to adverse, null or favourable wind conditions with regards to achieving critical velocity. The key aims when developing the ventilation modes were to:

1. Maintain the same operating strategy of the shafts between modes, therefore only requiring changes to the operation of the jet fans between modes.
2. Achieve a 15% overlap in the meteorological force bandings between adverse and null wind modes as well as between favourable and null wind modes. This is to avoid shifting between modes when the atmospheric conditions vary rapidly close to the limit of each ventilation mode.

To better understand the stability of the meteorological forces between tunnel portals, barometric pressure readings were recorded between two locations chosen to be representative of a typical long tunnel. The data was used to understand how frequently the modes might be changing and inform the design of the control system.

Keywords: Tunnel ventilation system, barometric pressure, barometric pressure stability

1. INTRODUCTION

The long tunnel that was analysed contained intermediate shafts roughly every three kilometres. These intermediate shafts contain a tunnel ventilation fan assembly, along with other supporting equipment. The functional requirement and spacing of these ventilation shafts are subject to relevant Code of Practice, tunnel operation constraints and local fire authorities' recommendations and are not the main subject of this paper.

The ventilation concept for the long tunnels was based on preventing back layering by achieving critical velocity in the incident bore and pressurising the non-incident bore to keep in tenable when the adjoining cross passage doors are opened. The ventilation concept requires the use of shafts in push/pull mode and jet fans located in the tunnel bore near the portals. For such long tunnels, the simplest ventilation design outcome is to mitigate against all barometric pressure differences using portal jet fans and then use the shafts in a conventional push/pull manner. However, for very long tunnels the barometric pressure differences can be so great that an impracticable number of portal jet fans is needed. The approach that might therefore be needed is to adopt as many portal jet fans is as practicable and 'over size' the shaft capacity to implement consistent ventilation modes regardless of meteorological forces However, this can lead to high airflow capacity requirements of the ventilation system which require airway connections to the tunnels with large cross-sectional areas to prevent excessive aerodynamic resistance and high air speeds on the adjacent walkways. In meeting these requirements can cause disproportionate construction risks and an increase in associated civil design costs.

This paper describes an investigation into the feasibility of using barometric pressure dependent modes with the view of lowering shaft airflow requirements. Initially, ventilation modes were developed for a range of shaft ventilation capacities and meteorological forces. A review found three distinct ventilation modes depending on whether the meteorological forces lead to adverse, null or favourable conditions with regards to achieving critical velocity. Favourable meteorological forces would occur with the pressure difference causes more flow to pass the fire, but it is important not to over ventilate in such cases to avoid flame spread, high walkway velocities or smoke going past an exhaust shaft. Adverse meteorological forces would make it more difficult to achieve critical velocity.

The ventilation modes were for smoke control purposes and the ventilation system capacity had been sized likewise. Normal, congested and maintenance operations ventilation modes are not discussed as the principles would be the same should their ventilation strategy be similar.

2. BAROMETRIC PRESSURE DEPENDENT MODES

Adverse, null and favourable candidate ventilation modes were developed using 1D modelling (the SES and now named SVS software) to assess against different portal to portal pressure differences. The design barometric pressure differences that might occur at the portal locations were identified by the national meteorological agency with the most challenging differences selected to occur not more than 1% of the year and corresponding to portal to portal pressure differences of around 250 Pa. The analysis included for other parameters that would affect the ventilation system performance such as ventilation direction (forward or backward with respective to traffic travelling direction), different incident location along the incident tunnel and included for open or closed cross passages (for dual bored tunnels). A key consideration was to find modes where there was a degree of overlap of pressure ranges where the design criteria could be met. The ventilation modes can be condensed to that shown in **Figure 1**.

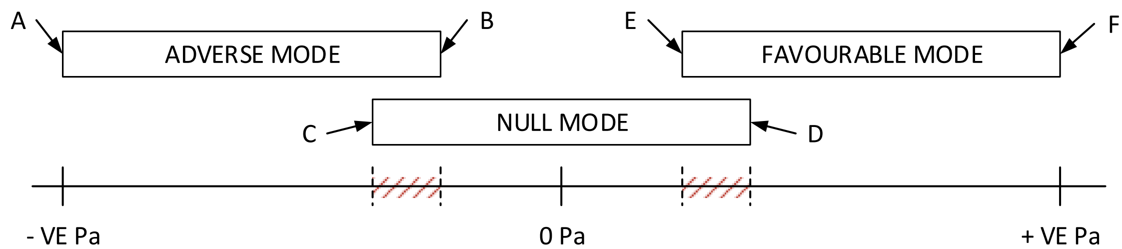

Figure 1: Ventilation modes schematic

The adverse mode was developed to control smoke across the pressure range between A and B (opposing the direction of ventilation). The null mode was developed to control smoke across the pressure range C and D (mildly opposing to mildly supporting the direction of ventilation). The favourable mode was developed to control smoke across the pressure range between E and F (supporting the direction of ventilation). The overlapping regions (C to B and E to D) were set to cover 15% of the total range for which the ventilation system was design (pressures A to F). The margin was intended to act as a buffer to minimise the potential for the ventilation system to change between modes during operation. The consequence of this happening is discussed in Section 3 of this paper.

A final set of ventilation modes were selected such that they were as similar as possible. Null modes made use of a combination of the shaft ventilation fans and jet fans located at tunnel portals to meet the design criteria. Adverse and favourable modes used the same shaft operating modes with the use of a greater or fewer number of jet fans to meet the tunnel ventilation design criteria during more favourable or adverse pressure differentials. Therefore, it was not required for any shaft ventilation system that was operating to change state when transitioning between modes. The use of jet fans allowed for the shaft ventilation system operating capacity to be reduced, potentially, by up to half when compared to the shaft only ventilation system. This led to smaller shaft to tunnel airway cross-sectional area requirements.

A benefit of this was that system reliability could be increased while reducing the spatial requirements of the ventilation equipment. For example, a ventilation shaft fan system could reduce from a duty/duty/standby to a duty/standby arrangement (from 3 to 2 fans, albeit the capacity of each of the fans was higher). Another benefit of the ventilation capacity reduction was to the civil design, smaller airway size requirements and less installed ventilation equipment enabled the civil designs to also get smaller. This would reduce construction risks and provide potential cost savings especially when the shaft and tunnel are in poor ground conditions.

One limitation of this approach is the need to actively monitor the changes in barometric pressure. The stability of the barometric pressure would be key to avoid quickly changing between ventilation modes. Failure to do so may results in unintended ventilation system performance, the potential for equipment damage, a potentially confusing situation for the Operators at Control Centre as well as unduly dynamic situation for the fire and rescue service. A study on the barometric pressure stability would be discussed in Section 3 of this paper.

The control system would need to be more complex than previously owing to it having to receive the barometric pressure readings and give active control of the ventilation modes, such as from a PID controller. This may be done through the tunnel SCADA system where the rolling average pressure could be calculated at regular intervals, such as every 15 minutes, to prevent undue hysteresis. The tunnel SCADA system would determine which pressure banding the tunnel system was in and use this data to automatically modify the sub modes during a fire incident.

3. STABILITY OF BAROMETRIC PRESSURE

Detailed and synchronised data of barometric pressure changes over commensurate length tunnels were not available. To understand better the stability of the meteorological forces between tunnel portals, experimental barometric pressure readings were recorded over similar length distances representative of typical values for the long tunnels.

The pressure data was recorded using a BMP280 pressure sensor and processed using an Arduino. **Figure 2** shows the setup for the Arduino. Two pressure recording devices were used, representing one at each tunnel portal. The pressure sensors measured the absolute pressure at each location; however, the ventilation modes were determined only by the barometric pressure difference. Therefore, the pressure data was standardised to sea level. The recording frequency of the measurements was every 30 seconds. The duration of all pressure tests undertaken was five days. The pressure readings were compared to online weather data, which had a frequency of 30 minutes, and showed good agreement (see Figure 3). The difference shown were due to hydrostatic pressure. The weather was reported to be fair in Day 1 and Day 2 before reported to be rainy in Day 4 (Worthing Weather, 2019).

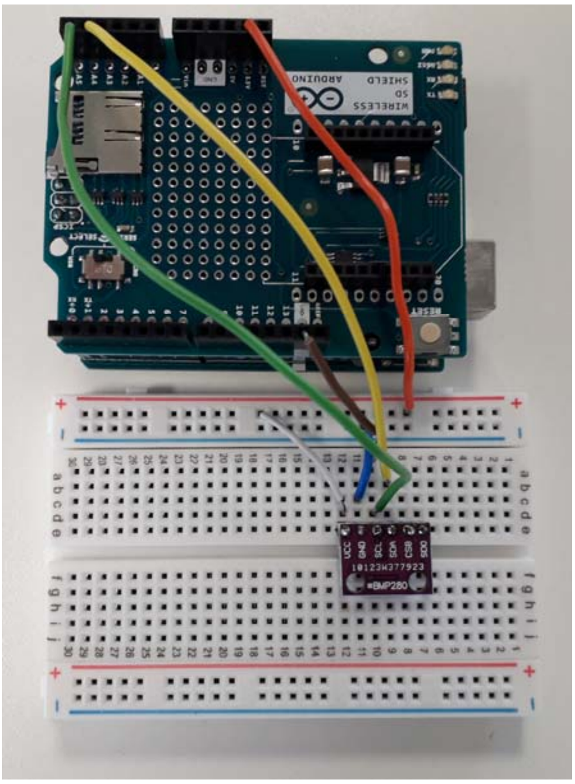

Figure 2: Pressure Sensor

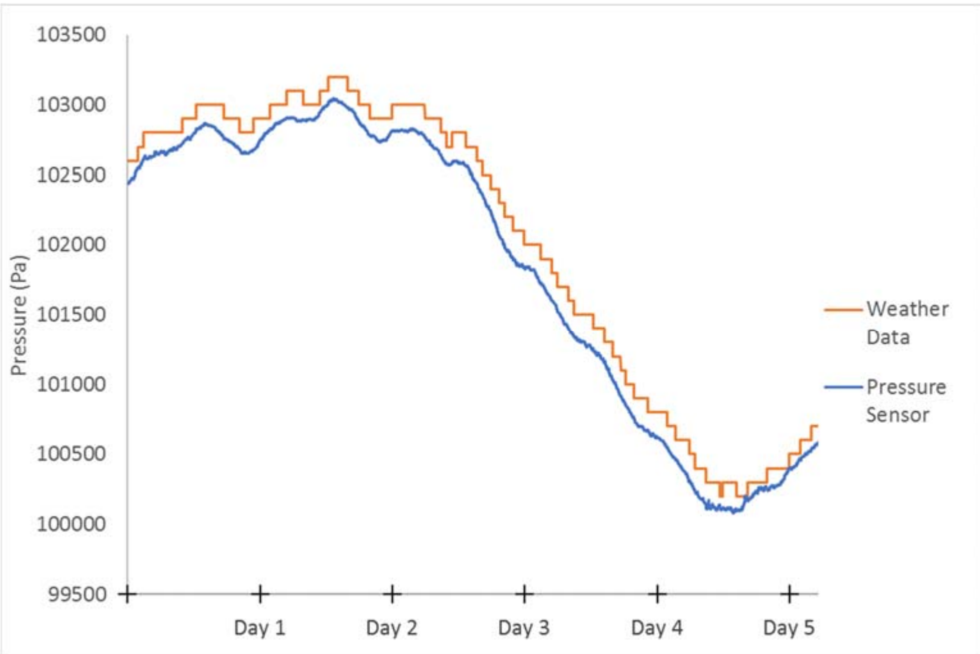

Figure 3: Weather data against recorded data

Two sets of data were collected. One set of data was between two locations 8.5 km apart. This distance was chosen as a representative length of a long tunnel. The other set of data was between two locations 55 km apart. This set of data was chosen to provide a more challenging case. This is because for locations separated at greater distances, there is a higher likelihood that the two locations will be experiencing larger differences in weather conditions, meaning that the barometric pressure difference between the locations would be greater.

Referring to **Figure 1**, the adverse mode was between pressure points A and B, with A representing the 99th percentile barometric pressure difference for adverse conditions, and B calculated as 25% of that value. The favourable mode was between pressure points E and F, with F representing the 99th percentile barometric pressure difference for favourable conditions, and E calculated as 25% of that value. The null mode was between pressure points C and D, with those values representing 40% of points A and F respectively. This gave an overlap region between ventilation modes equal to 15% of the 99th percentile pressure values. For the 8.5 km sample, the pressure points A and F were chosen based on meteorological office data for a representative long tunnel, with values of -225 Pa for A and 149 Pa for F. For the 55 km sample, the pressure points A and F were chosen as the maximum and minimum pressure differences over the five-day period, with values of -257 Pa for A and 150 Pa for F.

For both sets of data, the analysis attempted to replicate the control system for the ventilation system to see how often the ventilation mode would be changed. A recording frequency of 10-15 minutes was assumed to be reasonable to inform the ventilation control system without any unintended consequences such as negative feedback of the system or potential for equipment damage. The following shows the analysis methodology:

1. The initial operating mode was established from the initial barometric pressure difference at the start of the test.
2. For each subsequent 15-minute timestep, the ventilation mode for that time step was determined based on the barometric pressure difference.
3. For each time step, the updated operating mode was selected by comparing the acceptable ventilation modes for the current timestep to the operating mode from the previous timestep. Where practicable the null ventilation mode was selected as preferable.

For example, if the acceptable ventilation modes at the current time were in the overlap region of null or favourable, and the current ventilation mode was null, the ventilation mode in operation remained as null. If the current acceptable ventilation mode was favourable only, and the current ventilation mode was null, the operating ventilation mode would change to favourable. **Figure 4** shows a visualisation of the barometric pressure data for the 8.5 km data set over the five-day period. On the figure, horizonal lines have been drawn to represent each of the pressure points indicating mode change as specified from Figure 1.

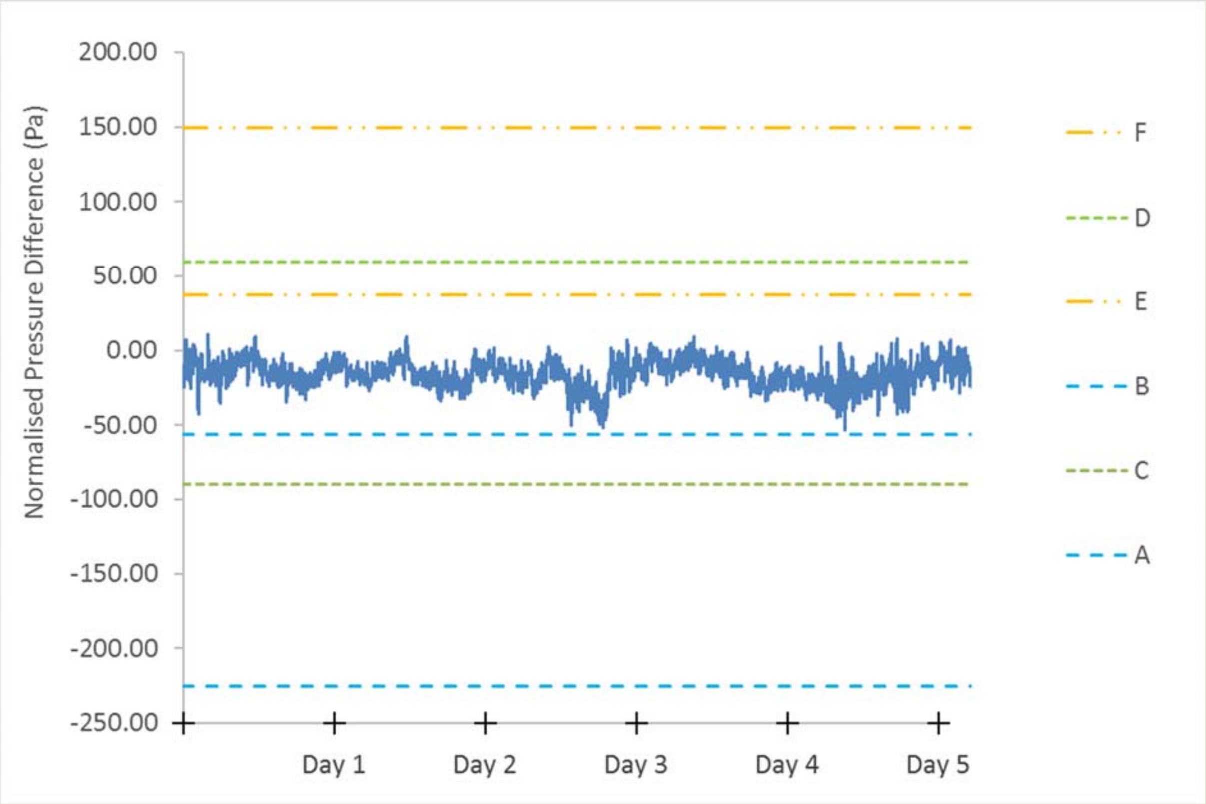

Figure 4: 8.5 km Barometric Pressure Difference with Time

The results from the 8.5 km data set predicted that over the five days the ventilation mode would not change. The maximum change in pressure recorded over the period was 2.67 Pa/min. At this rate it would take 8.4 minutes to cover the entire overlap region and force a second ventilation mode change. The 99th percentile pressure gradient was recorded as 1.41 Pa/min. At that rate it would take 15.8 minutes to traverse the overlap region. Also, the calculation of the second derivative over a 15-minute period gave a maximum value of 0.63 Pa/min^2, therefore it was predicted to be unlikely for the pressure gradient to completely reverse and then traverse the overlap region within a single 15 minute period, requiring a change in ventilation mode.

Figure 5 shows a visualisation of the barometric pressure data for the 55 km data set over the five-day period. Similarly, to the previous figure, horizontal lines have been added representing the mode pressure points. Also, circle markers have been included representing the times where a mode change would be required to change.

Figure 5: 55 km Barometric Pressure Difference with Time

The results for the 55 km data set predicted that over the five days 17 mode changes were required. The shortest duration between mode changes was 52.5 minutes. The maximum rate of change in recorded pressure difference was 3.21 Pa/min, at this rate it would take 7 minutes to minutes to cover the overlap region. The 99th percentile pressure change was 1.79 Pa/min which would take 12.6 minutes to traverse the respective overlap region. Calculation of the second derivative gave a maximum value of 0.66 Pa/min^2, therefore it was predicted to be unlikely for the pressure gradient to completely reverse and then traverse the overlap region within a single 15-minute period, causing the need for a second mode change.

4. SUMMARY AND CONCLUSIONS

Barometric pressure dependent ventilation modes may be beneficial under certain design situations which include spatial challenges in the ventilation shafts or adjoining adits making the transmission of large ventilation flow rates challenging. Such conditions may arise due to civil constraints such as from poor ground conditions that gives preference to reducing the ventilation capacity within the shafts of long tunnels.

In order to achieve an acceptable outcome, reduction in the number of shaft ventilation fans was supplemented using jet fans installed at the tunnel portals and active control of the ventilation system during an emergency during pressure dependent modes. This paper considered the development of three ventilation modes per emergency scenario based on the barometric pressure difference between tunnel portals: Null, Adverse and Favorable such that the design criteria for the tunnel ventilation was still achieved. The ventilation modes were developed such that there was an overlap region between adjacent modes equal to 15% of the 99th percentile pressure values. Furthermore, any change to the operating mode only required changes to the jet fans operating with the ventilation shafts operating in the same configuration between all three modes.

In adopting these modes, the ventilation control system would need to actively monitor the changes in barometric pressure between tunnel portals to inform the selected ventilation mode. Changes to the operating ventilation mode depended on two factors, the initial operating point, and the change in pressure with time. The risk of unstable barometric pressures could cause unintended ventilation system performance, the potential for equipment damage, a potentially confusing situation for the Operators at Control Centre as well as unduly dynamic situation for the fire and rescue service.

The most challenging scenario would be if the conditions were fluctuating about an overlap region. To better understand the stability of the meteorological forces between tunnel portals, experimental barometric pressure readings were recorded over a 5-day period for two pairs of locations. Based on the calculated maximum change in pressure over the five days, it would take seven minutes to cover the entire overlap region. Therefore, it would be plausible shortly after activating the ventilation system and between sample points to require a mode change. However, this is considered very unlikely based on the distribution of the data.

The measured data showed that at a rate of change equal to the 99th percentile of pressure gradients recorded, the time duration before a single mode change would be required could be as short as 11.1 minutes, therefore a sample frequency between 10-15 minutes was expected to be sufficient for the majority of conditions and reasonable for the tunnel ventilation system. Calculation of the second derivative of pressure with time concluded that it would be very unlikely for subsequent mode changes to be required shortly after the first. This would require the pressure gradient to completely reverse and then cover the overlap region all within a single sample period.

The analysis predicted there is a plausible scenario that one mode change would be required between sampling points. If this were to happen then the system could be operating a ventilation mode with too little or too much capacity for a maximum period of 10 to 15 minutes depending on the sample frequency. During this time, there may be failure to achieve criteria. The existence and severity of the failure would depend on the fire location, however, as the ventilation mode would be operating just outside its pressure range close to the overlap region, any criteria failure was expected to be minimal. After 10-15 minutes, conditions would begin to improve once the system activates the required operating mode.

5. REFERENCES

Worthing Weather. (September 2019). Von Time and Date UK: https://www.timeanddate.com/weather/uk/Worthing/historic abgerufen