Role of variable speed drives in safe, reliable and sustainable tunnel ventilation

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ABSTRACT: The urbanization is expanding. By the end of the century, 50% of the world's population will be urban. Cities and their infrastructure grow rapidly. This also applies to tunnels and metros. The important aspect in such projects is ventilation. Ventilation ensures wellbeing of tunnel users in normal situations and provides safety in case of emergencies.
Active ventilation is based on air movement via a fan wheel run by an electrical motor. To control the air flowrate, direction and pressure, variable speed drives are used. They are a vital part of ventilation as they help ensure process efficiency, reliability and tunnel safety.
Ventilation typically consumes a lot of energy used by a tunnel, so drives are often employed to increase tunnel energy efficiency and decrease operating expenses. Drives adjust the fan motor speed based on the vehicle fumes concentration, therefore saving energy.
In case of a fire, drives make smoke control flexible. They regulate fan speed and rotation direction to ensure smoke stratification and combat backlayering for safe evacuation. Fire in a tunnel implies fast response from ventilation and smoke extraction systems. Drives provide prompt fan start, stop, rotation direction change which are the key requirements in tunnel ventilation.
Active front end drives go beyond fan speed control. They ensure power quality eliminating disturbances in the network, for reliable ventilation. It is important for long tunnels with weak power supply and long cabling. This type of drives also contributes to the tunnel sustainability, as power quality affects power network equipment sizing. The drives allow to decrease e.g. electrical generator size by 50% or transformer size by 20% – a huge input to the carbon footprint reduction.

1 INTRODUCTION

1.1 *Tunneling market*

According to various studies *(Business Research Insights, Tunnel and Metro Market Size, Share, Growth and Industry Growth by Fan Type – Axial Flow Fans and Jet Fans, by Application – Tunnel and Metro, Regional Forecast 2022 – 2028, 2021)*, the global tunnel and metro market is forecasted to grow at a CAGR of over 8% during next 10 years.
This means increased human and vehicle traffic and increased requirements towards tunnel and metro user safety as a result.
Additionally, environmental burden increases as infrastructure is a massive consumer of energy to maintain all its engineering systems functioning. So, making infrastructure as sustainable as possible and minimizing its impact on the environment is crucial as well.

1.2 *Tunnel and metro engineering systems*

To make sure tunnel infrastructures are safe, multiple aspects need to be covered by tunnel engineering systems. Thus, power supply systems maintain the rest of the systems up and running.

Ventilation systems ensure air quality inside the tunnel – remove particles, car exhaust, excessive heat to provide better visibility and comfort for the tunnel users. In case of emergency, they can act as smoke exhaust and pressurization systems to maintain safe escape routes / safe waiting spaces and provide the access to the place of fire for firefighters.
Fire extinguishing systems take care of fire mitigation via activating water sprinkles near the fire.
Water drainage systems also play a huge role in ensuring the safety of tunnel users. They are especially critical in underground and underwater tunnels, removing water intruding into the tunnel infrastructure on a constant basis or, for example, in case of occasionally happening storms.
Lighting systems in tunnels ensure a good visibility for car/people better recognition and safe traffic. They can navigate tunnel users in case of emergency, being part of the evacuation strategy.
Video surveillance systems allow operators to foresee hazardous situations and act ahead to prevent those or send an immediate help if an emergency occurs.
This paper will focus specifically on tunnel ventilation systems and will explain how the automation and control technology – variable speed drives – allow to make tunnel ventilation safer, while mitigating the impact on the environment at the same time.

2 TUNNEL VENTILATION

2.1 *Tunnel ventilation system types*

Before diving into the tunnel ventilation automation and control techniques, it's good to familiarize with the most common tunnel ventilation system types from the design perspective.
Longitudinal tunnel ventilation type implies the airflow along the tunnel length. Air enters and leaves the tunnel usually through tunnel portals. In some cases in can be done through dedicated shafts.

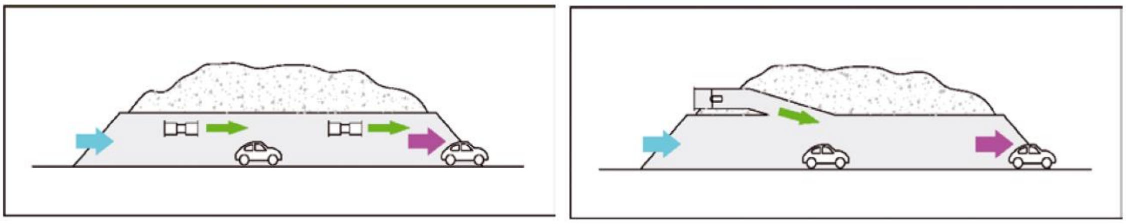

Figure 1. Longitudinal ventilation types with jet fans and Saccardo nozzle respectively *(Road Tunnels: Operational Strategies for Emergency Ventilation, PIARC Technical Committee 3.3 Road Tunnel Operation, 2011).*

Transverse tunnel ventilation systems imply the airflow entering and leaving the tunnel in a distributed way – through dampers situated along the tunnel length. The semi-transverse one is different the way that the air enters through dampers and leaves through portals or vice versa.

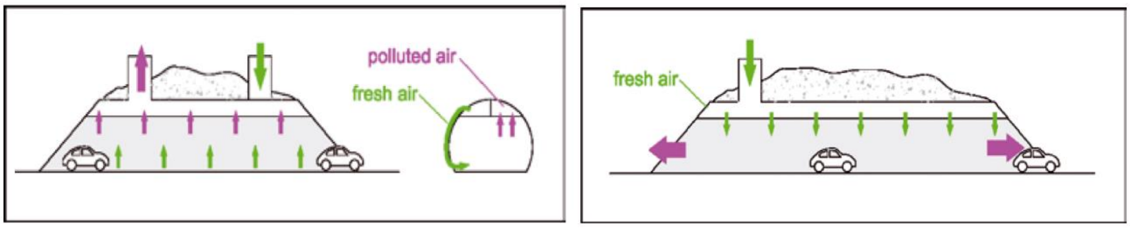

Figure 2. Transverse and semi-transverse ventilation types respectively *(PIARC, 2011).*

2.2 *Tunnel ventilation modes*

We'll review in brief two tunnel ventilation modes here – normal ventilation and ventilation in case of fire emergency for longitudinal, transverse and semi-transverse ventilation system types.
For a longitudinal ventilation system in the normal mode, fresh air enters the tunnel through a portal/shaft, moves along the tunnel length, and leaves from another portal/shaft, removing car exhaust, dust and excessive heat from the tunnel. If the tunnel is unidirectional, this usually

happens in the direction of car movement. The air quality along the tunnel is not uniform, which results in a higher pollution at one of its ends.
In case of emergency, longitudinal ventilation systems do not have a great flexibility. If bidirectional jet fans are used, the smoke can be blown out from the portal closest to the source of fire or in the direction opposite to the congestion of cars, depending on the situation and the safest way to act.
With transverse and semi-transverse ventilations, the ventilation strategies are different and more flexible. In the normal mode, the fresh air enters the tunnel evenly through a system of dampers distributed along the tunnel. This ensures a better air quality along the whole tunnel length. The polluted air can be removed evenly through distributed dampers as well or e.g. through a dedicated shaft in the middle of the tunnel or tunnel portals.
But the most important aspect is how transverse and semi-transverse ventilation systems behave in case of fire emergency. They are more flexible comparing to longitudinal ones as they are able to extract the smoke (and heat) precisely through dampers around the place where it is generated, without spreading it along the tunnel length in the direction of the closest portal or shaft, and without the risk of intoxicating tunnel users not being in the immediate proximity to the fire source.

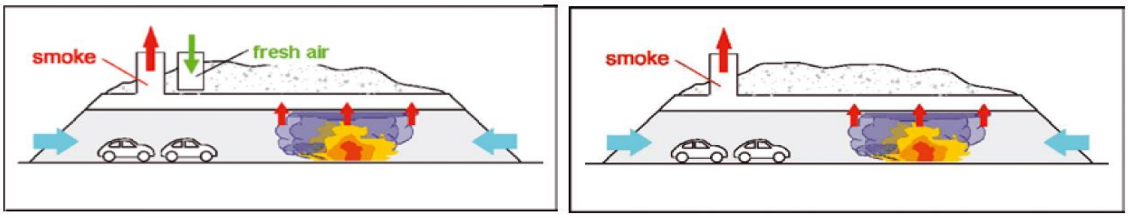

Figure 3. Transverse and semi-transverse ventilation in case of fire emergency *(PIARC, 2011).*

3 VARIABLE SPEED TECHNOLOGY AND ITS ROLE IN TUNNEL VENTILATION

3.1 *What is a variable speed drive*

Variable speed drive or variable frequency drive is a technology employed for controlling the speed of rotation and torque of an electrical motor. This is required in order to match the need of the application run by the motor. It happens through drives changing motor input frequency and voltage. The side benefit is energy savings as the motor does not always need to run 100% of time with 100% speed and torque.
First prototypes of variable speed drives – VSDs – were patented at the beginning of the XX century, but the technology has received a massive development since then.
Variable speed drives are placed between the electrical supply and the motor running some application (fans in case of tunnel ventilation).

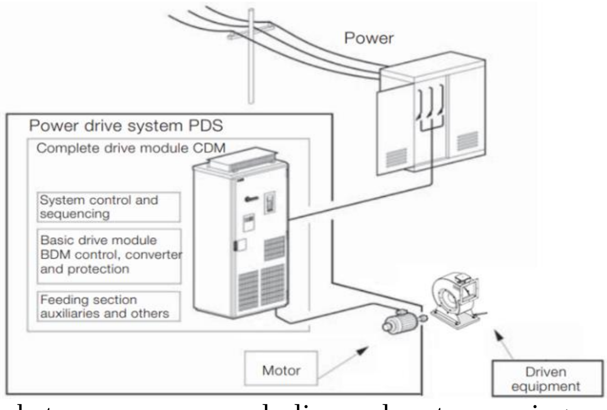

Figure 4. Drive locates between power supply line and motor running application *(ABB Drives 2018, Technical Guide).*

What the drive does, it converts the power flowing from the electrical supply to a motor. The drive design in a nutshell consists of a rectifier converting AC power to DC power, which then flows into capacitors, making, in their turn, the power waveform smooth. After capacitors, power goes through an inverter changing DC power back to AC power and adjusting current frequency and voltage according to the application needs before the power gets into the motor. This means the motor will not rotate with the nominal speed, but with the one required by the application at a given time. This is where massive energy savings happen.

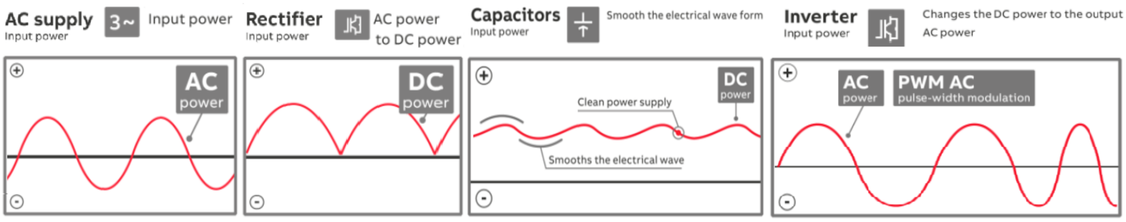

Figure 5. Working principle of a traditional AC variable frequency drive.

Although the main working principle is same, it’s good to understand that there are different variants (topologies) of the variable speed technology established in the market, with varying effect around the application control, power quality in the network, braking capabilities and so on.

3.2 *Drive’s role in tunnel ventilation*

This section is dedicated to reviewing the role of variable speed drives in the most important aspects related to tunnel ventilation design – safety, process reliability and sustainability. Depending on the drive technology chosen, these aspects can be significantly improved.

3.2.1 *Energy savings*

Important to know that ventilation in tunnels is often one of the most energy consuming systems that can easily account for over 15% of the total energy used by the tunnel (Fig. 6). Variable speed drives help to ensure substantial energy savings in tunnel ventilation. It happens thanks to adjusting fan motor speed to tunnel needs.

Thus, traffic jams in road tunnels generate much car fumes and excessive heat, affecting visibility and comfort of the tunnel users. Sensors detect the particulate matter, temperature, CO2 increase and send this information to the tunnel control system or ventilation drives directly, so the drives know that the fan motor speed should be increased to cope with the poor air quality and evacuate extra heat and contamination from the tunnel. But during non-rush hours, tunnel ventilation doesn’t need to be intense and run at 100% load. Getting the information on low concentration of particles, heat and exhaust in the tunnel, drives decrease the speed of fans accordingly, which allows to save massive amount of energy.

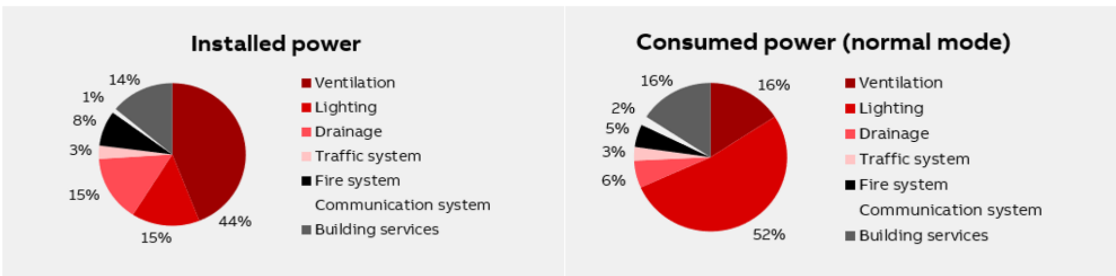

Figure 6. Power consumption in tunnels *(R. Dzhusupova, TUE 2012. Zero energy tunnel concept).*

3.2.2 *Safety in case of emergency*

We have reviewed the most common tunnel ventilation types and modes (normal/emergency) in Chapter 2. Let’s familiarize with how variable speed drives can improve safety in case of fire emergency.

Initially drives control the speed of fan motors. When a fire occurs in a tunnel, drives can help fans become part of the smoke/fire suppression strategy, varying the speed and direction of fan rotation to support the evacuation of tunnel users, extract smoke and provide the access to the emergency spot for the firefighters.

When tunnel systems identify a smoke/fire in the tunnel, the tunnel ventilation and its components incl. drives enter the emergency mode. The smoke management strategy depends on many factors like the tunnel design (uni- or bidirectional, if there are evacuation spaces along the tunnel length), the ventilation system type, etc. In general, longitudinal ventilation systems require more complex strategy to manage smoke and this is where drives can be helpful.

For example, if the fire happens in a long congested bidirectional tunnel, it is often recommended to extract the smoke through the closest portal. The World Road Association (PIARC, 2011) prescribes to run the fans with a velocity below 1.2 m/s in the beginning of fire emergency. This will help to maintain smoke stratification under the ceiling and allow more time for safe evacuation under the smoke layer for tunnel users.

Once the evacuation is completed, increasing the air speed to critical velocities of over 2.5 m/s (PIARC, 2011) allows to blow the smoke away entirely, avoiding backlayering (when the smoke spreads against the airflow direction). This allows firefighters to safely approach the fire spot from the upstream side and start extinguishing it.

This all explains the criticality of using variable speed technology on tunnel fans, when the ever-changing situation requires different modes from tunnel ventilation.

3.2.3 *Emergency mode implementation in drives*

It important to separately clarify how the emergency response can be implemented in drives due to the fact that the design of the drive's emergency mode, so-called fireman's override mode, might differ depending on the drive manufacturer, and there is no product specific standard for the mode.

When specifying the drive technology for a project where the emergency response is needed, it must be made sure that the drive can answer the smoke extraction / evacuation route maintenance needs of the tunnel.

The override mode itself means that the drive will override (ignore) all non-critical faults and warnings when being in this mode and basically run the controlled application until destruction as the main goal is people's safety and not the equipment integrity.

Non-critical faults and warnings can be, for example, overtemperature which in normal situation negatively affects the drive's electronics and causes its premature aging and subsequent failure, but in case of emergency this is not something to be prioritized, so the drive will keep running tunnel ventilation fans. At the same time, critical faults and warning might include overcurrent. Ignoring this fault can cause an extra fire in the tunnel and this cannot be allowed, so the drive will stop.

It is also important to make sure that the drive in the override mode has the ability maintain variable speed of the controlled fan and adjust it based on the information coming from the tunnel automation system depending on the fire location and the stage of fire.

3.2.4 *Process reliability*

It is critical to maintain tunnel ventilation process continuity, both in normal and emergency situations, and variable speed drives can contribute into this aspect as well. Besides standard drive features, like the ability to softly start and stop fans without mechanical and electrical shocks for tunnel ventilation and power supply systems respectively, there are some more drive features to consider.

Thus, drives can monitor the performance of a fan bearing, one of the weakest points in the system, alarming when it is about to break. In this case the motor starts drawing a higher current for the same load due to increased resistance in the bearing, and the drive will notice this.

One the most frequently seen problems in tunnels in voltage drop over long cables. In practice, it means that the nominal power won't be delivered to the application, and it won't be able to run full load. In case of smoke extraction fans, it means that the extraction capacity will be reduced, which might have a negative effect on the tunnel users' safety.

Drive technologies with active front end (transistors instead of standard diode-based rectifiers) with DC bus capacitors in their design allow for compensation of the voltage drop and ensure the nominal power on the fan application end, so safety is not sacrificed *(ABB Drives 2019, Active front end drive technologies).*

One more benefit of this specific drive technology (based on active front end) is that it does not create disturbances in the power network called electrical harmonics. Let's clarify this particular moment. The working principle of variable speed drives includes repeating switching actions in the rectifier. This generates electromagnetic noise, harmonics, in the supplying network. If the harmonics content is too high, it can negatively affect the power network components, both from overheating and electromagnetic interference perspective. This can lead to their malfunction and failure.

Harmonics can be managed with add-on corrective equipment, but it's always better not to generate them in the first place, choosing the advanced fan speed control technologies like active front end drives. Thus, when selecting a variable speed control for a tunnel fan, it also does make sense to evaluate how it affects the power network, supplying this fan, so negative consequences can be avoided in the future.

3.2.5 *Sustainable design*

Sustainability consists of multiple aspects. We separately discussed the efficient energy use in tunnels, tackling one of the most energy consuming systems – ventilation. But there is more in sustainability. From the material usage perspective, the smarter the design of tunnel infrastructure can be, the less carbon footprint the tunnel can leave at its construction stage. Let's review how such a specific component as tunnel automation and control solution can affect the tunnel design and why it is important to have holistic approach when choosing tunnel system components.

We just discussed how active front end variable speed drives do not generate electrical harmonics in the tunnel power network comparing to standard rive solutions. It meant much for the power network reliability, but it means a lot also for the tunnel design.

One of the common ways to cope with harmonics is to apply filters or oversize power network components to mitigate the unwanted effects. In practice it means bigger generators, transformers, switchgears and other power network equipment and bigger spaces to host it as a result. All this leads to increased carbon footprint of the tunnel infrastructure.

Different equipment manufacturers have different guidelines on oversizing their equipment to cope with harmonics in the network. E.g. for transformers, there were common guidelines established by Underwriter Laboratories (UL), a global independent safety science company *(Underwriters Laboratories 1991, Proposed requirements and proposed effective dates for the first edition of the standard for dry-type general purpose and power transformers, UL1561).*

There was the K-factor established to reflect the harmonics conditions – the higher it is, the higher is the harmonics content in the network and the less the carrying capacity of the transformer is (the more it needs to be oversized). The standard drives have a K-factor of 20 according to UL, while active front end drives have a K-factor below 5. Figure 7 shows how it affects the transformer capacity and how the transformer needs to be oversized when going with a standard drive solution instead of the active front end one.

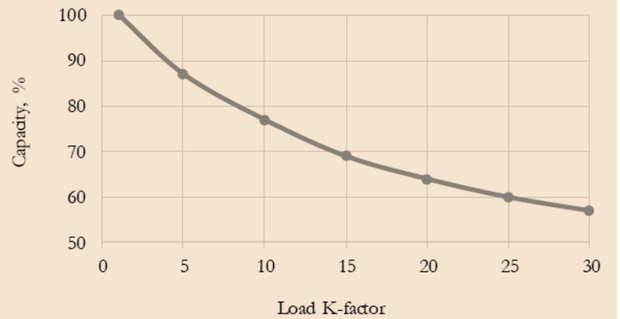

Figure 7. Transformer derating based on the K-factor *(Underwriter Laboratories, 1991)*.

Similar principles apply to generators frequently present in tunnels as a standby source of energy, as well as other power network components.

But there can be considerations not only around power quality, but also other aspects affecting the design of tunnel systems. Thus, it's commonly known that tunnel ventilation projects often

are very precise about the time needed to stop fans completely or change the direction of their rotation – it should happen in seconds in case of emergency to avoid unnecessary smoke spread in the tunnel space. For this, various fan braking techniques can be used.
Often those are based on resistors, when fan braking energy is dissipated in the form of heat. The installations are complex, often requiring the usage of massive cabinets to place brake choppers and resistors. Additionally, the cabinet air conditioning is needed. All this negatively affects the infrastructure carbon footprint. There can be various alternatives, but the one mitigating installation complexity and saving space is, again, an active front end drive with regenerative capability, allowing to feed fan braking energy right back to the power network.

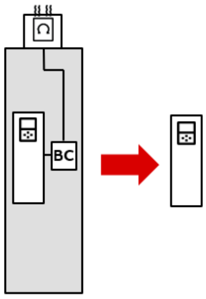

Figure 8. Traditional fan braking solution based on brake choppers (BC) and resistors vs. a regenerative braking solution *(ABB Drives 2018, Technical Guide 8 – Electrical Braking)*.

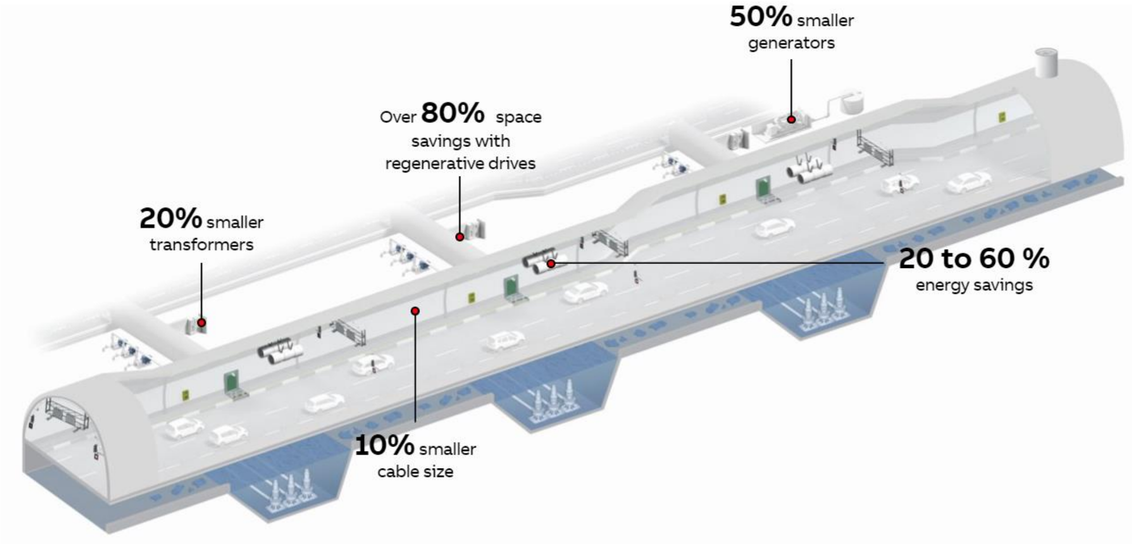

Figure 9. VSD technology effect on the tunnel design – practical example.

4 REAL CASE STUDIES

There are multiple case studies proving the importance of drives' role in tunnel ventilation. Even though their role in ensuring efficient energy use is clear, the focus point of tunnel projects is safety.
The tunnel under the Ursynow district is a critical point in Warsaw's southern ring road. It has over 2-kilometer length and connects sections of the A2 highway forming a part of the Trans-European Transport Network. It was opened in 2021 and employs variable speed drives as part of tunnel ventilation system. To ensure safety of the tunnel users, the drives were tested with fans to comply with EN 12101-3 standard "Smoke and heat control systems - Part 3: Specification for powered smoke and heat control ventilators (fans)" covering drive-controlled smoke and heat extraction fans and ensuring the drive-motor-fan system can operate at high temperatures and deliver nominal airflow/extraction rate without the malfunction of any components.

Another massive project, the world's longest (57 km) railway tunnel Gottardo running through the Alps employs drives for efficiency and, at a greater extent, safety purposes as well. There is a requirement commonly seen in tunnel ventilation projects about being able to stop tunnel fans in seconds in case of emergency, so the fresh air wouldn't intensify the fire or move the smoke to smoke-free areas where evaluation could happen.
With the fresh air fans in Gottardo tunnel having an outer diameter of approximately 3.5 m it could have been challenging, especially taking into account limited space in the tunnel electrical rooms which makes it challenging to host cabinets with braking resistors and air conditioning. But the drives with regenerative braking capabilities were involved. They return fan braking energy in the form of power back to the electrical network and ensure that the large fans can stop in seconds without intervening in the smoke management strategy of the tunnel and providing the highest level of safety to the tunnel users.

5 CONCLUSION

The paper has introduced the situation in tunnel and metro infrastructure industry and dived into underground space engineering systems with a particular focus on tunnel ventilation types. The role of control and automation technologies for tunnel ventilation, namely variable seed drives have been reviewed. Depending on a variable speed technology chosen for ventilation control, tunnel safety and ventilation process reliability can be increased substantially.
Besides that, drives can have a significant impact on tunnel infrastructure carbon footprint. Other than natural for drives energy savings at partial ventilation loads, they can affect the design of tunnels, saving on power network equipment sizing and the spaces hosting such equipment, meaning smaller environmental impact for the tunnels during both construction and operation phases at the end.

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