

HEAT TRANSMISSION BETWEEN GROUND AND TUNNEL AIR FOR DIFFERENT CONFIGURATIONS AND USES

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ABSTRACT:

From exhaustive measurements of the temperature variation in different positions of different tunnels, the phenomena of heat transmission between ground and air are explained for different configurations, depths and uses of the infrastructure.

The tunnels for which temperature data are available over time at different points and for which the processes of heat exchange between ground and air are analysed based on their comparison with the outside temperatures and air velocities inside are: urban tunnel of great extension and complexity (M30), metro line (L1 Metro de Barcelona) and 24 km long mountain railway tunnel (in its stage prior to operation). This data is complemented by calibrated 1D CFD simulation models of these infrastructures that allow for a deeper analysis of these phenomena and additional situations that have not occurred.

From these analyses we can conclude that the transmission of heat between the ground and the tunnel is a phenomenon of great importance to obtain in the design stage the evolution of the temperature over time and its variation between winter and summer. These conditions can imply natural currents due to the chimney effect at certain times of the year or cyclical currents throughout the day and that in the tunnels in operation can be masked by the piston effect. As an example, on the M30 every night there are important natural currents in a fixed direction at each point even though traffic is very low and that even in many areas it is contrary to the direction of traffic. This phenomenon occurs in the same direction and similar values throughout the year and it has been proven that its reason is that at night the temperature in the tunnel is close to the average day and it is higher than the lower temperatures of the night, which causes chimney effects between portals of different heights due to air density variations.

Heat transmission is also quantified according to the depth of the tunnel and connection points with the outside. This allows to calculate the transition distances between the outside and the ground temperature.

Keywords: Tunnel ventilation, heat transmission, chimney effect.

1. INTRODUCTION

The temperature of a tunnel wall varies over time. This variation is affected by several parameters, including:

- Ground characteristics
- Tunnel depth
- Ambient conditions in the area
- Air currents
- Heat dissipated within the tunnel by passing vehicles or installed systems

In turn, the wall temperature primarily influences the air temperature in the tunnel. The difference between the air inside the tunnel and the outside creates aerodynamic forces (derived from the chimney effect due to the difference in air density). These forces can modify the sizing and operation of the ventilation system. This aspect can also be of great importance in cases where it is considered necessary to maintain the temperature within certain temperature ranges (such as in meters or air conditioning of technical rooms) or where these differences are to be used for HVAC of nearby buildings.

The process of wall temperature variation has a daily component (usually cooler temperatures at night than during the day) and a seasonal component (with higher temperatures in summer and colder temperatures in winter). Depending on the airflow moving through the tunnel throughout the day, the thermal inertia of the system will be greater or lesser between winter and summer. If air currents are low, the tunnel will behave similarly to a cellar, with a constant average temperature, which means it is colder than the outside in summer and warmer than the outside in winter. If the air current is very high, the tunnel could behave similarly to a home, where the interior temperature is close to the outside temperature and the wall temperature could be considered close to the daily average.

This paper analyses the importance of the various parameters and phenomena that influence wall temperature and how it varies throughout the day and year. It also examines the influence of this value on air currents and temperature in the tunnel, as well as its impact on ventilation.

2. MAIN EFFECTS

The temperature of the tunnel wall depends on the depth below the surface. It is generally considered that the surface temperature of a ground layer (up to about 10 m deep) is influenced by the outside temperature. At the surface, the temperature varies between the average temperature of the coldest month and the average temperature of the warmest month. Due to its thermal inertia, the temperature variation from one day to the next is very small. Beyond a certain depth (about 10 m), the temperature remains practically constant and practically equal to the average annual temperature of the area.

This ground condition is used by geothermal installations, which attempt to take advantage of the lower ground temperature in summer and higher temperatures in winter. These installations use the ground as a thermal accumulator. In summer, they inject heat (we could say they extract cold) which they recover in winter. If the system's temperature is not balanced between cold and heat, the ground tends to increase or decrease in temperature relative to its natural temperature, so the system would stop working (or decrease its efficiency) when the ground temperature is close to that of the outside.

The temperature distribution of the ground would be like the following figure:

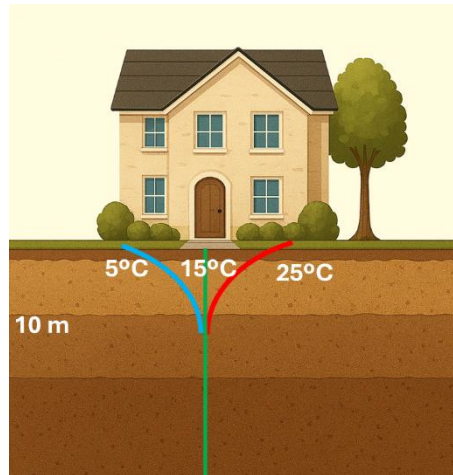


Figure 1: Ground temperature variation along the year with depth (Source Copilot)

At greater depths, the temperature of the ground increases because of geological pressure at values of around 25-30°C per kilometre.

The first time the tunnel is excavated, the temperature of the walls will be the same as that of the unexcavated ground. As time passes and the air movement processes inside the tunnel will cause variations in ground temperature. Depending on the amount of air exchanged with the outside world and the heat dissipated within the tunnel, these variations will vary daily or seasonally, with varying degrees of variation and shorter or longer periods of equilibrium. In this regard, it is worth noting that some deep tunnels include cooling systems to compensate, if necessary, for the high temperatures expected in the rock at the time of excavation. In principle, we can assume that a ventilation system that moves a large flow of air along the tunnel would be sufficient to modify the long-term rock balance to values close to the average temperatures in the area.



Figure 2: Thermal equilibrium will depend on the external, geothermal and ventilation conditions of the tunnel.

The ambient temperature in a given area typically varies daily and seasonally. Although the climate varies from year to year, we can assume that the minimum temperatures are around the average values of previous years.

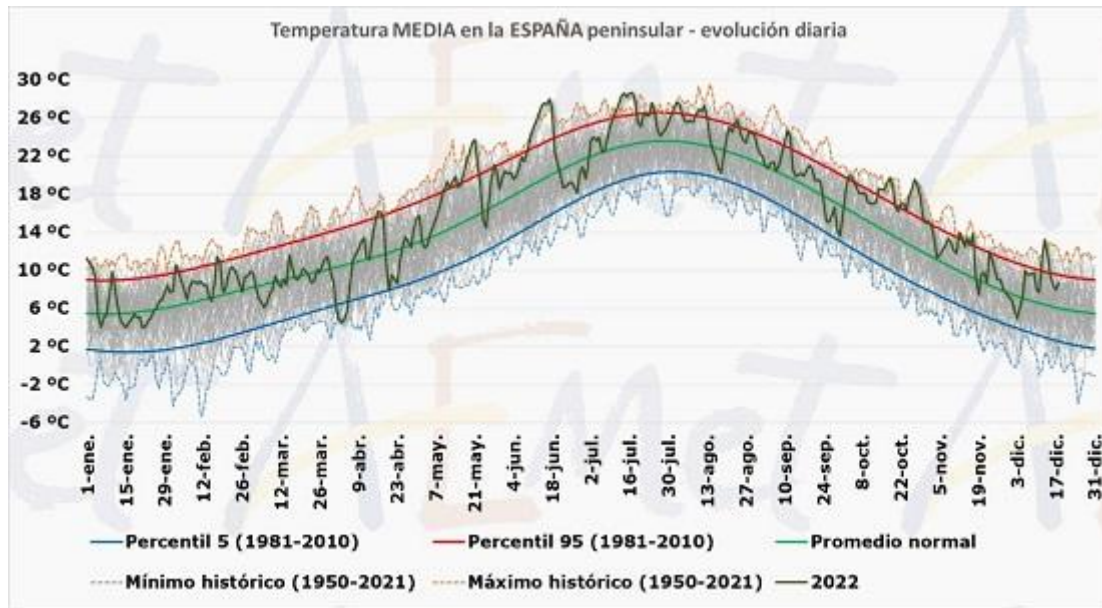


Figure 3: Annual temperature in Madrid (Source Aemet)

It is observed that a tunnel lags the outside temperature due to the thermal inertia of the ground. We will show various examples of this later in tunnels with different configurations.

In a cellar or tunnel with little air movement, the temperature will remain practically constant and close to the average annual temperature. This is because still air is considered good thermal insulation. In the case of rapid air movement, heat transmission with the walls is already higher. Furthermore, the continuous renewal of outside air implies (due to the temperature difference between the incoming and outgoing air) an exchange of heat with the outside, which modifies the temperature of the wall and the ground around the tunnel. Therefore, we will need to briefly explain the heating/cooling processes of solids and gases, as well as the heat transfer between solids and solids and between solids and gases, depending on the temperature difference and the type of transfer. Between solids and gases, it is very important to consider whether the air movement is shallow, laminar, or turbulent. These types of air movement are associated with heat exchange by conduction, or convection. Heat transmission by radiation will also occur, although generally to a lesser extent due to the small temperature differences between the walls and the air.

The equations for conduction are the following:

$$\text{Fourier's Law of Heat Conduction: } q = -k \times \frac{dT}{dx}$$

Where:

q: heat flux (W/m²)

k: thermal conductivity of the material (W/m·K)

dT / dx: temperature gradient

In gas-solid interactions, conduction is significant only in the thin layer of gas adjacent to the solid surface.

Table 1: Some examples of Thermal Conductivity

<i>Material</i>	<i>Typical k Value [W/m·K]</i>	<i>Notes</i>
<i>Concrete</i>	1.0 – 1.7	Common in tunnel walls and floors
<i>Air</i>	0.024 – 0.030	Thermal conductivity of air
<i>Steel (carbon)</i>	45 – 60	Used in reinforcements and structures
<i>Aluminium</i>	200 – 235	Used in ducts or panels
<i>Rock (granite)</i>	2.5 – 3.5	Found in natural tunnel environments
<i>Insulation (mineral wool)</i>	0.035 – 0.045	Used for thermal protection

The equations for convection are the following:

Newton’s Law of Cooling: $q = h \cdot A \cdot (T_s - T_\infty)$

Where:

q: heat transfer rate (W)

h: convective heat transfer coefficient (W/m²·K)

A: surface area (m²)

T_s: temperature of the solid surface

T_∞: temperature of the gas far from the surface

The value of h depends on whether the convection is natural (due to buoyancy) or forced (due to fans, pumps, etc.).

Table 2: Some examples of the Convective Heat Transfer Coefficient (Solid-Gas Interfaces)

<i>Situation</i>	<i>Typical h Value [W/m²·K]</i>	<i>Notes</i>
<i>Air flowing over a flat wall (forced)</i>	10 – 100	Depends on air speed and surface roughness
<i>Natural convection (still air)</i>	2 – 25	Occurs in stagnant zones
<i>Air inside ventilation ducts</i>	20 – 250	Higher with fans or forced flow
<i>Turbulent flow over heated surface</i>	100 – 1000+	Found in high-speed ventilation systems
<i>Air moving at 2 m/s</i>	H ≈ 30-50	

The amount of heat Q needed to increase the temperature of a substance (solid, liquid, or gas) is given by the formula: $Q = m \cdot c \cdot \Delta T$

Where:

Q : heat energy (in joules, J)

m : mass of the substance (in kilograms, kg)

c : specific heat capacity (in J/kg·K)

ΔT : change in temperature (in kelvin or °C)

Table 3: Specific Heat Capacity of Common Tunnel Materials

<i>Material</i>	<i>Typical c Value [J/kg·K]</i>	<i>Density (kg/m³)</i>	<i>Notes</i>
<i>Concrete</i>	840 – 1000	2300	Depends on composition and moisture content
<i>Air (at 25°C)</i>	1005	1,184	Common value for dry air at constant pressure
<i>Steel (carbon)</i>	450 – 500	7850	Lower than most building materials
<i>Aluminium</i>	900	2700	High for a metal, helps in heat dissipation
<i>Granite (rock)</i>	790 – 900	2600	Varies with mineral content
<i>Mineral wool (insulation)</i>	~840	30	Similar to concrete, but with low density

From all the above, and from the values measured in tunnels shown in the following chapters, we can deduce that at low speeds, air behaves as an insulator. With air speed higher than 1 m/s, common in tunnels, heat transfer between the wall and the air is high.

3. ANALYSIS OF TUNNELS IN OPERATION

Below we collect temperature variations recorded in various types of tunnels.

3.1. Urban tunnel

Air velocity and temperature records have been analysed in various areas of the Madrid urban road tunnel network (M30). The following figure shows the temperatures and velocities in the cut & cover area of Avenida de Portugal in the summer of 2021.

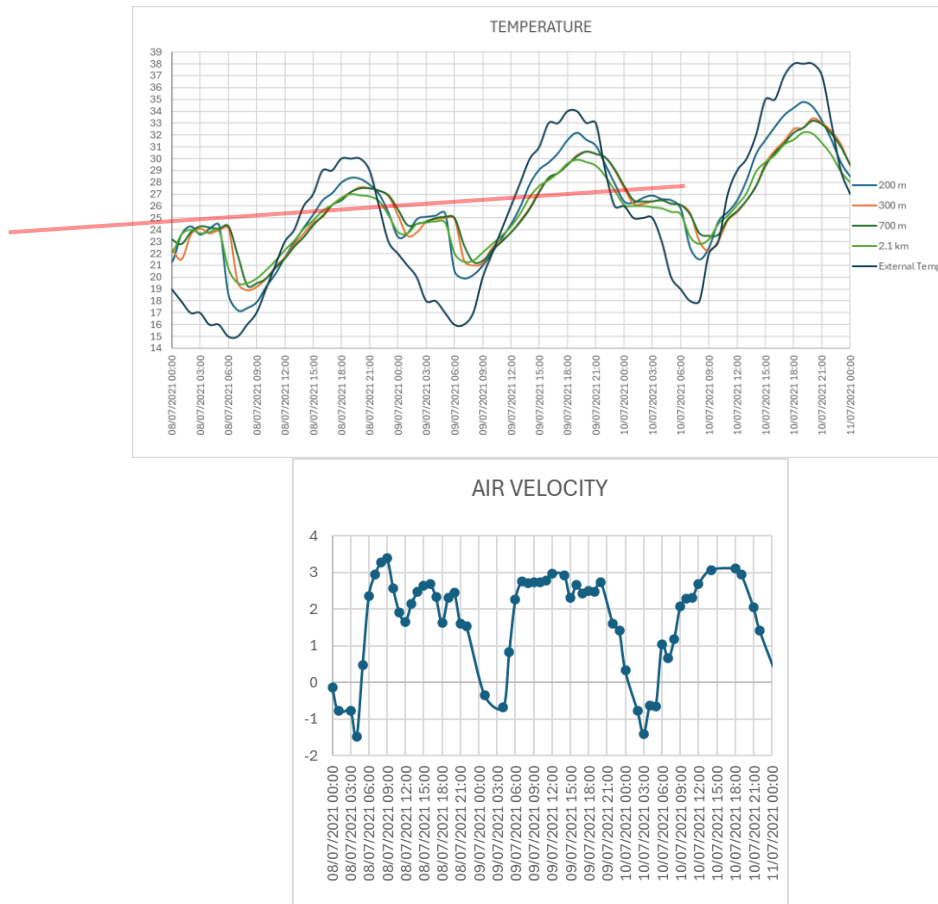


Figure 4: Temperature variation along the tunnel (with average evolution estimation) and air velocity

We can observe the following main aspects for this tube:

- There is a significant heat exchange between the walls and the air in the area near the portal.
- This exchange involves both heating and cooling the air depending on the temperature difference between inside and outside.
- During hours, when the outside temperature is lower than the inside and there is no significant piston effect, the air has natural draft in the opposite direction to traffic. Under these conditions, the temperature remains practically constant throughout the tunnel, at a value that could be considered the average for the infrastructure. This chimney effect can cause natural currents of the order of 2 m/s.
- The average temperature of the tunnel varies by up to 1°C from one day to the next, due to the summer period, when the infrastructure warms up because the average outside temperature is higher than that of the infrastructure.
- Thermal fluctuations reach 3°C in 200 m sections, with air velocities of around 2 m/s.
- Heat exchange with the walls is concentrated in the first 500 m of the infrastructure.

Considering the configuration and cross-section of this tunnel, whose area is about 100 m²:

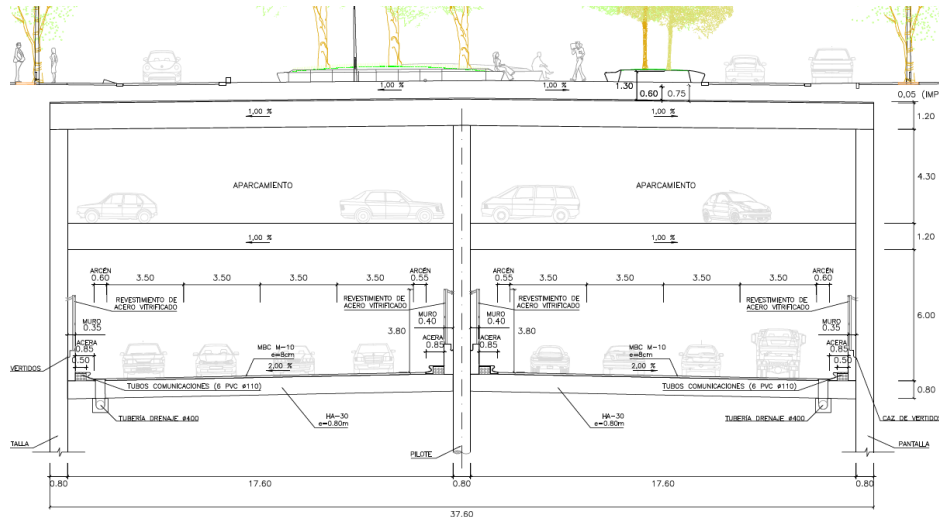


Figure 5: Typical cross section of the tunnel analysed

This implies a heat transfer in the portal area of approximately (during the hottest hours of midday and in 200 m length): $100 \text{ m}^2 \times 2 \text{ m/s} \times 1.184 \text{ kg/m}^3 \times 1005 \text{ J/kg} \cdot \text{K} \times 2 \text{ K} = 476 \text{ kW}$. If we consider this heat over the tunnel perimeter, in a 10 cm thick concrete layer, we obtain a temperature change of approximately: $476000 \text{ J/s} / (47.2 \text{ m} \times 0.1 \text{ m} \times 200 \text{ m} \times 2300 \text{ kg/m}^3 \times 840 \text{ J/kg} \cdot \text{K}) = 26 \times 10^{-5} \text{ K/s} = 0.94^\circ\text{C/h}$. This confirms the observation of the temperature variations shown in the previous figures.

If we analyse the air temperature variation along the tunnel, we will obtain a figure like the following:

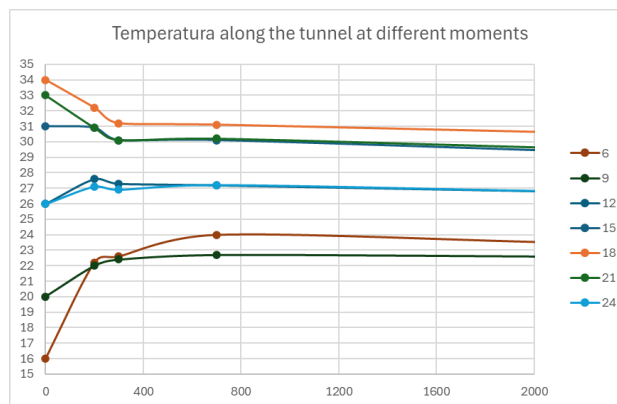


Figure 6: Temperature variation along the tunnel at the hours when the velocity is positive

We can observe a certain similarity between this distribution and the one mentioned above for the variation of the ground with depth, although in this case it does not converge on a constant value.

For more detailed analyses, it would be necessary to create a three-dimensional model of the tunnel and the surrounding ground, considering in this case that above the tunnel there is a parking lot that acts as insulation from the outside and the thermal conditions of the opposite tunnel. This model must consider the temperature variation of the tunnel structure, the heat transfer to the ground, and its storage capacity. 1D models analyse the transmission between the air and the tunnel and the temperature variation of the ground, although it is not easy to select the assumptions to be made (due to the lack of detailed knowledge of the ground conditions) nor to calibrate this for existing tunnels.

3.2. Metro tunnel

On Line 1 of the Barcelona Metro, an analysis has been carried out on the temperature evolution of the stations over time and its relationship with the outside temperature. The annual temperature evolution of a typical station is shown in the following figure in relation to the outside temperature:

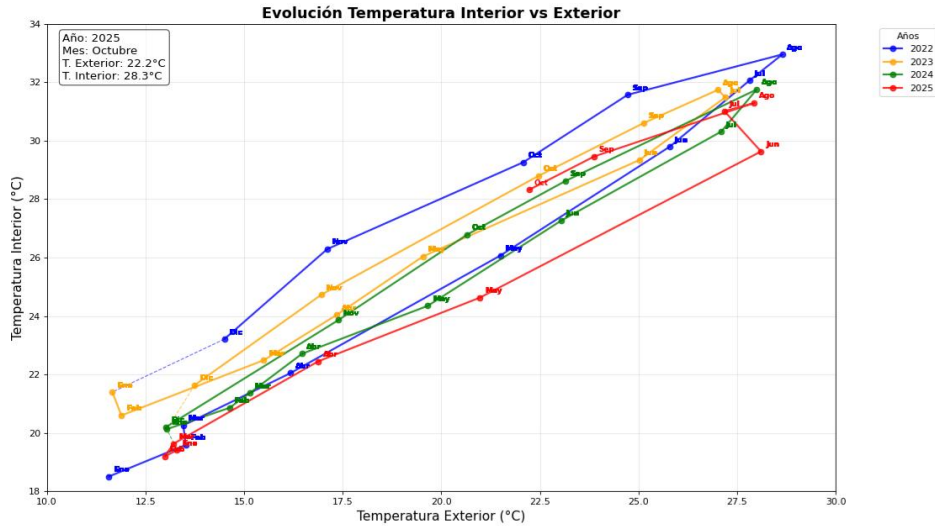


Figure 7: Temperature evolution of L1 of Metro Barcelona along different years.

The main temperature variation over the years in this case is due to the improvement of the ventilation algorithm, which applies Artificial Intelligence. With lower energy consumption each year, it optimizes the moments when outside air is introduced with the greatest temperature difference between outside and inside, to maximize the thermal storage capacity of the ground.

The daily temperature evolution of this line can be observed in the following figure:

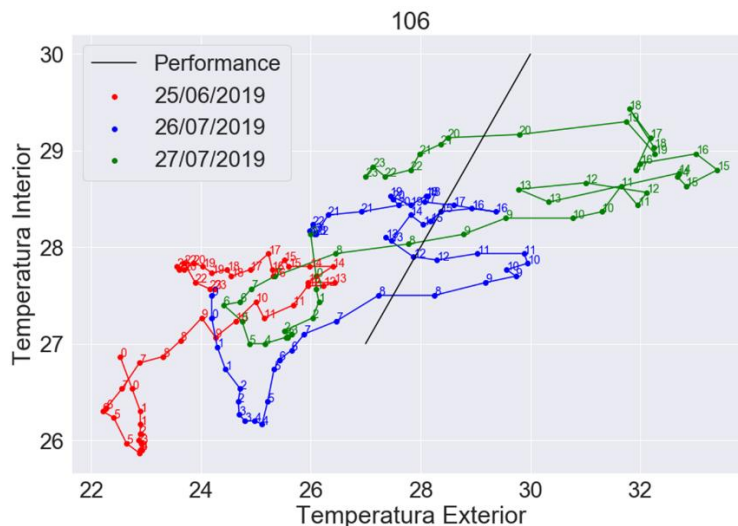


Figure 8: Temperature evolution of L1 Metro Barcelona along some days.

It can be observed that we have a similar evolution to that of the urban tunnel. The daily temperature of the tunnel varies similarly to the outside temperature, although with less variation due to the thermal inertia of the ground. In this case, the internal heat emitted by

No temperature differences were observed due to the depth at which the tunnel was located.

External temperature variations only impact the first few meters from the portal, with a length of approximately 2000 m. The rest of the tunnel remains at a practically constant temperature.

In this case, variations in air speed and direction are influenced by temperature, but mainly by atmospheric pressure differences between the valleys connected by the tunnel.

4. SUMMARY AND CONCLUSIONS

Heat transfer between the air and the tunnel walls is significant when air currents exceed 1 m/s. This effect is mainly concentrated at the portals due to external temperature variations and their difference with the tunnel interior. The external influence zone is limited to a few hundred meters. In many cases, longitudinal air currents will occur without the need to activate ventilation, due to the piston effect of vehicles, temperature differences between the interior and exterior if the portals are at different heights, or climatic differences between both ends.

In the variation of the tunnel's interior temperature, daily and seasonal cycles are observed. By appropriately activating ventilation during periods of greater temperature difference between the interior and exterior, the infrastructure's temperature can be modified.

This phenomenon also involves the heat dissipated inside the tunnel (either by vehicles or installed systems), although this value is usually relatively constant during tunnel operation.

The variation in interior and exterior temperature can cause air currents (due to the chimney effect from density differences), which must be considered in the design of the ventilation system, as well as in its control algorithms.

The thermal inertia of the tunnel and the heat transfer to the ground have a damping effect in relation to external temperature variations.