Yokohama National University

Doctoral Thesis

Development of Heat Transfer Model inside Urban Highway Tunnel under Vehicle Thermal Effect

都市内道路トンネル内の車両排熱からの熱移動モデルの構築

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Abstract

A highway tunnel in Tokyo experiences high inside temperature, especially during summer season, which can cause dissatisfaction of motorbike drivers. To overcome this issue, heat transfer need to be clarified. This thesis proposes a 1D approach to explain the heat transfer inside the tunnel based on literature review and simple calculation using the data collected from field measurement. Vehicle heat was roughly calculated by fuel consumption of observed traffic volume. Traffic-induced flow(piston effect) was studied by determining the flow field inside tunnel, using theoretical equations. Heat transfer coefficient to wall was calculated and verified by measurement data. Road surface heat was studied by temperature sensors applied on real site. In a certain range of tunnel, the amount of heat absorbed by road surface and concrete wall, extracted by ventilation system and went out by tunnel exit, were calculated respectively in short time period. These results are used to verify a heat-balance model to determine each proportion of vehicle heat dissipated in road, concrete wall and outside air. Finally, cooling measure based on this is preliminary discussed.
Keywords: *heat transfer*, *tunnel ventilation*, *traffic flow*, *fuel consumption*, *piston effect*

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Chapter 1

Introduction

The underground transportation system plays an important role in many major cities around the world. In Tokyo Metropolitan Area (TMA), the railway accounts for the largest share of passenger transportation. It also has more than 230 km of urban expressways (toll roads) and streets in central Tokyo area, a lot of which are usually under traffic control to ensure smooth operation. However, most main roads are almost always crowded, causing economic losses and environmental burdens. More than 10 million automobiles have been registered in the TMA, which will generate a huge amount of NOx, other air pollutants, and excessive noise. Construction of new tunnels and bridges is underway to improve capacity in the ring roads, which can disperse the excessive traffic concentration, and reduce the congestion dramatically on the Metropolitan Expressway in the city center section. It also enhances the social and economic benefits.

The Yamate Tunnel is one of such projects, which is one part of the Central Circular Route (C2) of the Shuto Expressway in Tokyo. It starts from the Takamatsu on-ramp in Toshima to the Ōi Junction in Shinagawa. The overall tunnel length is around 18.2 km, the second-longest in the world. Lying 30 m below the earth's surface, about 70% was constructed by the tunneling shield method. The roadway consists of two lanes in each direction.

Before building such big projects, many problems such as concerns about environmental issues, difficulties in purchasing right of land usage and opposition from local residents need to be resolved, which takes a long time from conception to completion [1].

After these problems have been solved, large infrastructure such as highway road tunnel can be built in the urban area. The increase of vehicle transportation load will have a negative effect on the driver comfort and sometimes even driving safety inside(frost or condensation on the back mirror when entering the tunnel). To eliminate the adverse effect, highway road tunnel designation should take operation efficiency, passenger comfort, and safety as the first priority. The Yamate tunnel has many operational and safety-related facilities. Among them are emergency telephones, fire-safety equipment, and cameras at certain intervals. Emergency exits leading to a separate emergency path are located no more than 350 m apart, there are Stairways lead up to Yamate Street. A duct running parallel to the roadway supplies fresh air and removes the exhaust. Dust-collection systems are designed to remove 80% of particulates from the air. Mist spray jets in several spots and sprinkler truck running through under certain schedule are also applied, however not enough efficiency during the hot season.

To optimize the comfort design, it is important to understand the characteristic of airflow and heat transfer inside the road tunnel. In the early days of subway and other underground transit system design, almost no consideration has been taken on the ventilation system [2]. The only mechanical ventilation inside is the airflow generated by moving vehicles. In most cases, additional facilities are needed to increase the flow rate inside the tunnel to alleviate passenger discomfort and safety problems [3].

In the modern design of the ventilation system inside the subway, passenger comfort and safety are well-considered. Temperature rising and airflow must be concerned. But for road tunnel where vehicles are running in, only pollutant extraction is mainly focused on to ensure air quality inside, emergency scenarios such as fire accidents are also considered. However, Temperature rising problems can also be very serious. The Yamate Tunnel is too hot inside during summer, the highest air temperature can be up to 48.3°C at midday, which is obviously over normal level for the motorcyclist and sometimes even hard for vehicle's air-conditioning to operate normally. Figure 1.1 shows the image of temperature distribution during a cool season.

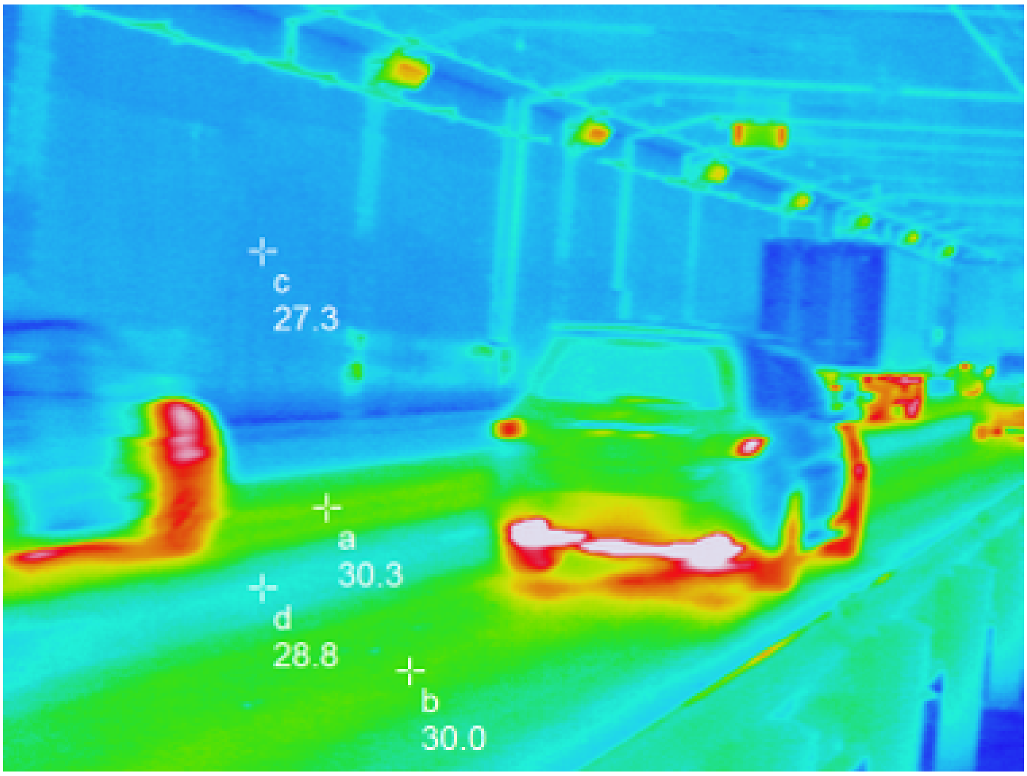


Figure 1.1: Temperature during early spring inside tunnel

When Vehicle travels through a long tunnel, a significant amount of heat has been given out due to fossil fuel combustion. In short, Everything from that is liberated from fuel-burning(gasoline or diesel) is finally dissipated as heat. The major part goes with exhaust gas and the other goes in

- cooling water system
- heating up of lubricate oil
- aerodynamic frictional energy when driving
- rolling friction between road and tire
- heat dissipated at transmissions/joints/brake

These parts also eventually turn in to frictional heat and heating up of the environment and vehicle themselves. The chemical potential energy in fossil fuel is fully dissolved in the environmental heat sink. Vehicle heat is the main contribution of temperature rising problems inside the long-distance tunnel. This energy either transfer tunnel structure(such as concrete wall and asphalt road) or being extracted by the ventilation system and piston effect. The energy transfer to the tunnel wall is important since soil temperature surrounds the tunnel will increase under continuous vehicle heat. So the ground is not good for heat dissipation and only absorb a small portion of heat [2]. This may need additional cooling measures to deal with high air temperature inside. The Channel Tunnel and Seikan Tunnel already applied countermeasures such as traffic restriction and cooling plants.

Generally, in case of a short and medium road tunnel, temperature rising problem is not considered because of its limited traffic volume, and heat generated by running vehicle can be easily dissipated either into surrounding earth or outside environment via the exit. However, for long tunnel such as the Yamate Tunnel with high traffic volume in the hot season, especially during congestion time, temperature rising issues cannot be ignored. Actually, because of bad heat dissipation inside the tunnel, temperature increase along tunnel axial direction with the traffic-induced wind. In previous research [4, 5], heat transfer in underground railway system was studied, as a result, periodical passing train generated the most heat load inside tunnel, heat balance model and several parameters were determined afterward.

It is therefore very important to make a good prediction model for these components of energy transfer when designing so that thermal problems in the tunnel environment may be solved. In the past, many types of research have been made to study long-term train tunnel temperatures but it is difficult to model the heat transfer to the train body. Some workers chose to ignore this energy transfer because the temperature rise in the train is not significant [6]. In the 1980s, Iguchi et al. [7] analyzed Seikan Tunnel temperature problems using periodical train heat release and constant illumination heat as main heat load, and they found the highest temperature near entrance near Hakodate should be considered. Providing more ventilation can release the exit rising temperature but increase the temperature in the middle part of the tunnel. Some researches such as [8, 9] studied underground train systems by a parametric study using 1D and 3D CFD model. Mortada et al. [8]built a model using the specific commercial software IDA Tunnel to simulate the London subway system temperature problems, they found that the key factors that influence the temperature were the cooler wall, regenerate train brake and ventilation volume. Saito et al. [10] studied the heat transfer through air and concrete wall by calculation, and then verified using experimental methods. The difference between this 2 outcome was less than 1°C.

However, the previous prediction model is not able to make reliable predict, therefore a more comprehensive heat transfer prediction model is required. In the case of vehicle tunnel heat transfer, 3 features need to be considered.

Firstly, vehicle heat needs to be roughly calculated. Secondly, there is a parallel relative motion between the vehicle surface and tunnel wall, which will determine the heat transfer properties between vehicle and tunnel structure. Lastly, heat dissipated in the air, i.e. heat extracted by a ventilation system which can be determined by field measurement data, and piston-effect can also bring out a large amount of heat through exits which will cause an air temperature increase in the axial direction.

In this study, more complicated road traffic heat are studied. First, airflow caused by piston-effect is primarily studied, this velocity profile is then used to calculate the convective heat transfer coefficient of concrete wall and road surface. Temperature distribution of road surface and concrete wall inside are measured in several spots along the tunnel, traffic volume and ventilation operation details are also collected. 2 types of vehicles: passenger car and medium truck [11] which representing general types on road are measured by field tests to know the vehicle heat. These results are used to build a heat-balance model [12,13], and verified using real measurement data. Finally, a cooling measure is discussed based on the model and verified using real measurement data.

Chapter 2

Literature Review

2.1 Traffic heat

At present, only a few research are done on the assumption of traffic generated heat. Some are related to fuel consumption and harmful gas prediction. To estimate fuel consumption, 2 approaches have been applied according to the previous study [14]. One is to use experimental methods which are directly measured by fuel consumption device. With the development of automobile technology, vehicle parameters during driving can be collected by an electronic control unit(ECU) via the controller area network(CAN). These data can be used for the fuel consumption calculation. Although measurement using fuel consumption meter can provide accurate data, it is difficult to massively use to get general information due to economic reasons. The carbon balance method is also difficult to determine each vehicle's size and emission amount.

The other method of studying fuel consumption is by making prediction models [15]. These methods can be classified into 4 types: a model based on engine power, driving behavior, speed-acceleration, and power demand. The last model is based on vehicle-specific power(VSP) which is most commonly used in recent years.

2.2 Ventilation system

The ventilation system inside vehicular road tunnels usually can be classified into Transverse and longitudinal. In these systems, the piston effect caused by moving traffic and jet fans is the main [16, 17].

Next, to travel time, the fuel consumption and the associated emissions of CO_2, hydrocarbons, or particulate matter, are essential factors when estimating the societal costs associated with vehicular traffic. On the most macroscopic level, fuel consumption is usually determined by multiplying the average consumption of a representative vehicle fleet (per kilometer or mile) with the estimated overall traffic performance in a certain period (vehicle-kilometers or vehicle-miles). For determining the influence of traffic congestions on the consumption and emissions, however, this method is not sufficient because the fuel consumption depends strongly on the velocity profile.

2.3 Ground Heat Absorption

Although the surface of the ground is largely subjected to daily and seasonal temperature fluctuation, the underground temperature tends to remain around a constant number of [18, 19]. Take the underground temperature of Tokyo as an example, the average temperature is between 15°C to 17°C around 10m below the surface. The tunnel is built through the underground, in most cases below 10m, so it can be assumed that underground soil temperature is nearly constant all year-round.

However, the soil is not contacted to tunnel air because the concrete wall and fire prevention board are built inside. As it is known that concrete is not a good material to conduct heat, with a heat conductivity around 0.6 W/mK. If additional fire prevention is installed inside, it may even weaken the process of heat transfer from inside to surrounding soil.

Sadokierski [5] introduced analytic solutions to airflows, heat convection, and heat conduction problems inside a railway tunnel. By using standard turbulent modeling assumptions, flow profiles and heat transfer coefficient were obtained in an open tunnel and annulus between the tunnel wall and moving train. He also found that the correlation between the fluctuations of heat transfer coefficient and air temperature will increase the surrounding soil temperature.

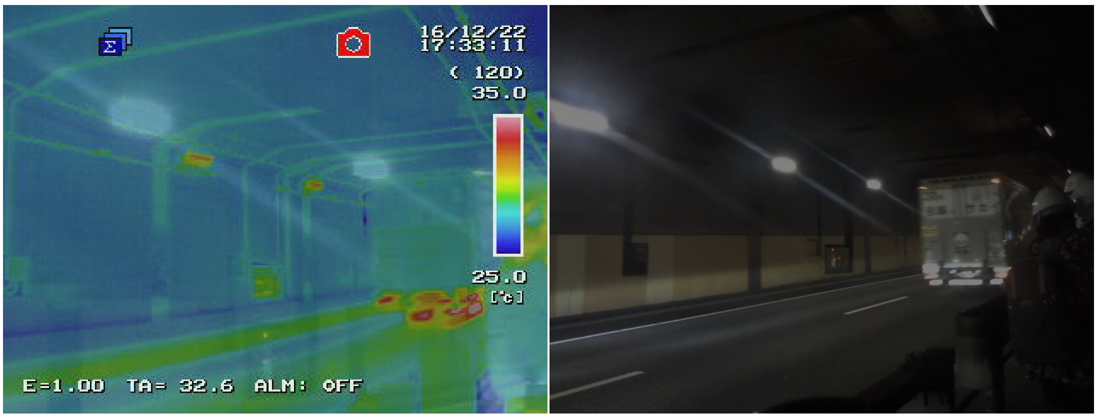
2.4 Road Surface Absorption

Road surface heat transfer was also been studied but not so many. Fujimoto et al. [12] introduced a heat-balance model in an open environment(accessible to sunshine and natural wind), to predict the road surface temperature under the thermal effect of vehicles. He found the vehicle thermal contribution to road surface temperature is not negligible. However, no research has been carried out to study inside road surface temperature. Prusa et al. [20] developed a conceptual model to study vehicle thermal effects on predicting frost/ice road conditions. Under heavy traffic conditions or stopping scenarios near intersections, vehicle heat could not be neglected.

Chapter 3

Heat Generated inside the Tunnel

To make sure what we are discussing here, it is important to mention again that the over-heat problem is very serious in the Yamate Tunnel during the summertime. So what is the main heat source lead to this bad situation? As an underground tunnel is built in an enclosed earth environment, it is not easy to influence by outside factors such as sunshine and wind on the ground. So the main factor is traffic generated heat, which causes this problem. The vehicle can generate a huge amount of heat during operation, not so many researchers have been working on topics related to vehicle heat because it varies from different types, sizes, and conditions. So vehicle heat is random, it is difficult to make a model to calculate how much heat generated by vehicles in real life. Figure 3.1 shows that even during the cold season, it was still hot inside the tunnel.



(a) Thermal image

(b) Normal photo

Figure 3.1: An example of temperature distribution inside tunnel near 21.6kp

However, it can be derived from common sense that those fossil fuel consumed by each vehicle will eventually be turned into heat energy. Most of them will be dissipated through ambient air, the rest of them will remain in the vehicle body. From Wikipedia, we can know that passenger car diesel engines have an energy efficiency of up to 41% but more typically 30%, and petrol engines of up to 37.3%, but more typically 20%. The efficiency is not that high for both engines, usually, around 30% is converted to power, even this amount of heat is finally all dissipated as heat energy through friction in the transmission system and tire, air drag and sound wave. Sound waves almost always generate a little bit of heat as they travel and almost always end up as heat when they are absorbed. Anyway, except those heat remained in the vehicle body and one part of them becoming potential energy due to different elevation, all the rest of it will finally turn into heat. Probably higher than 95%, though no useful experiment and simulation can be able to demonstrate this idea. So in this study, all the fossil fuel burned inside is assumed to finally converted into heat. Heat source now can be simplified into prediction on fuel consumption by vehicle fleet, which is also a difficult topic.

It is not easy to study exactly how much energy does a certain distance of real traffic flow is consumed, due to the reason that each vehicle in on the road may be different, varies from light cars to heavy trucks. They certainly have different gasoline/diesel consumption rate. There is no actual study on this due to totally randomness and less meaning. Some researchers [21, 22] use the VSP model to predict certain kinds of vehicle energy consumption.

3.1 Traffic Volume

Traffic Volume plays a very important role to determine the heat rate. In this model, traffic heat are calculated per 1m length. When traffic density is high, vehicle heat also increases.

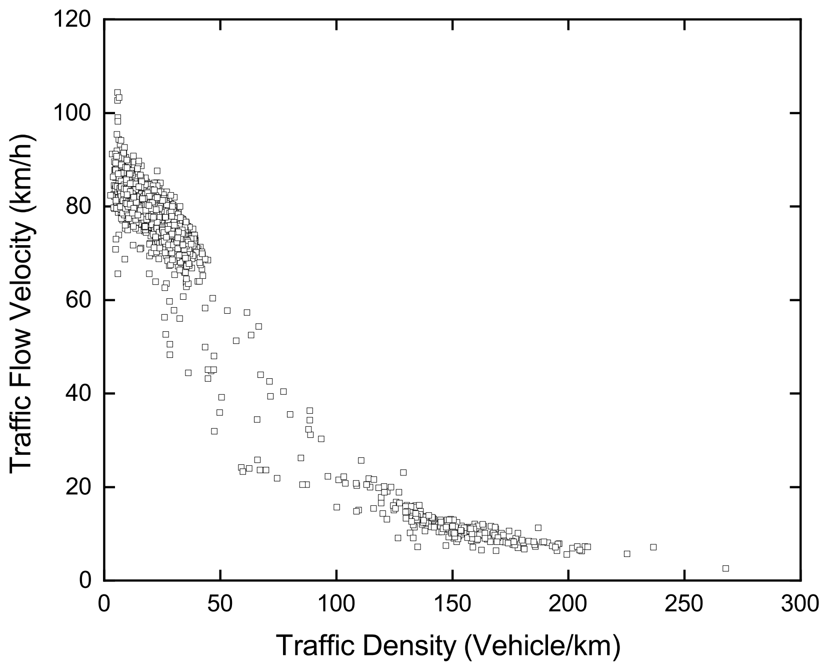


Figure 3.2: Traffic density and velocity

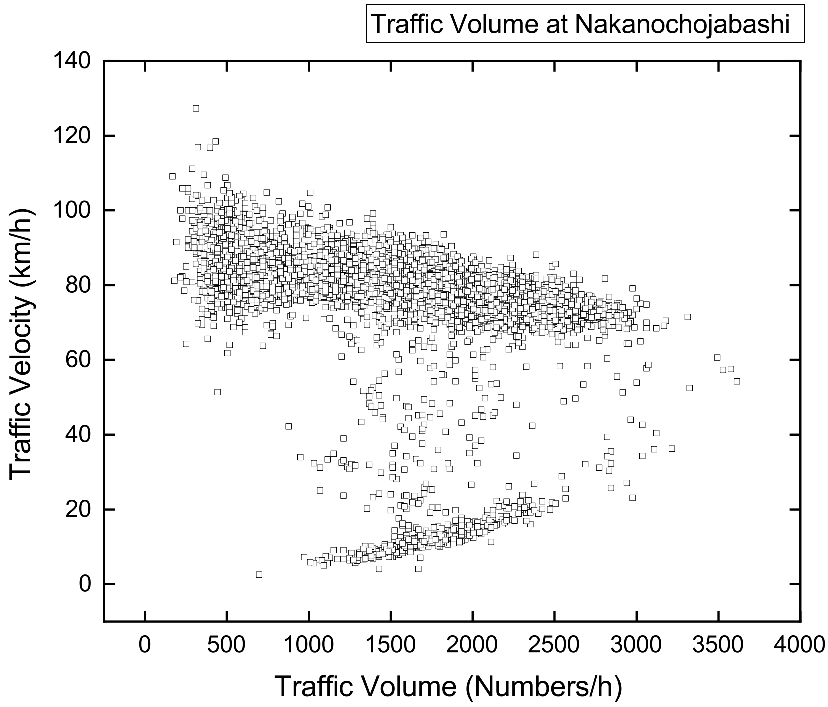


Figure 3.3: Traffic volume and velocity at Nishiikebukuro

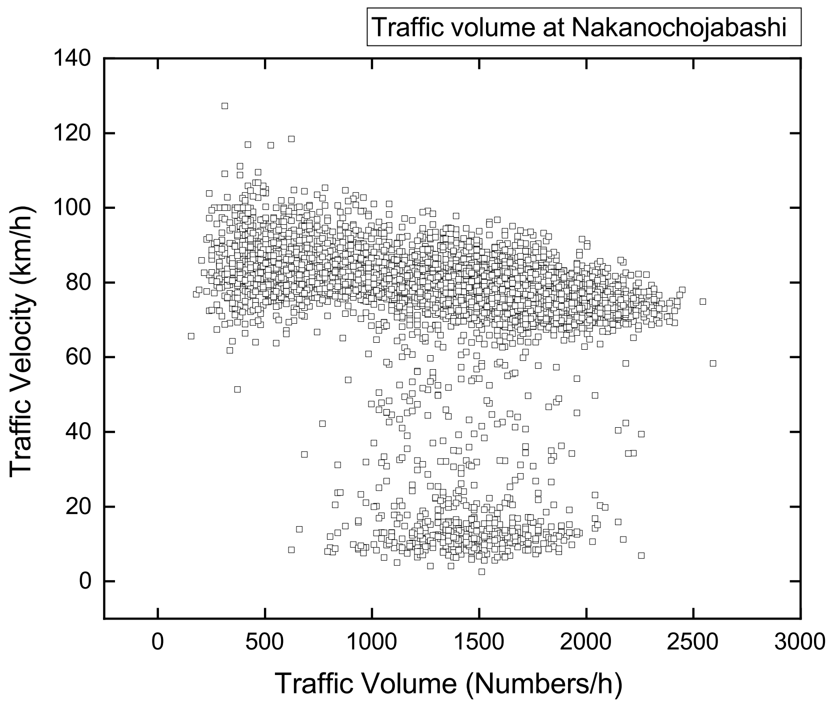


Figure 3.4: Traffic volume and velocity at Nakanochoja

In figure 3.5, vehicle generated heat and other parts are demonstrated. Left side is on 19.89kp (km position), and right side on 21.58kp, clockwise ring. Traffic direction wind velocity is induced by traffic flow which will be discussed later. So the exist of vehicle can be treated as heat source which give out heat continuously along road direction, and traffic direction wind inducer.

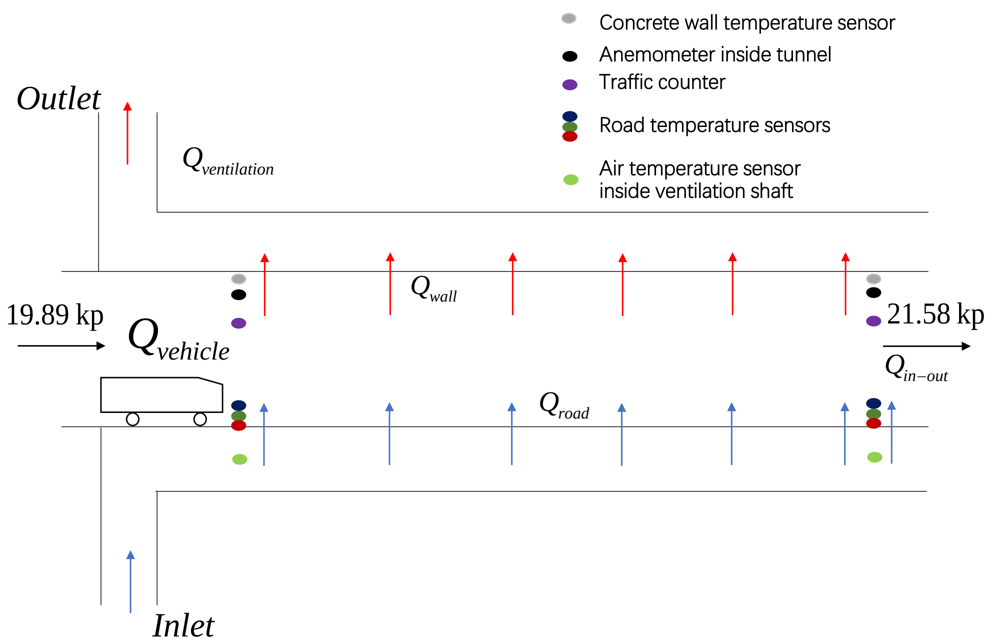


Figure 3.5: Heat transfer model inside tunnel

3.2 Vehicle Generated heat

Vehicular traffic can generate a huge amount of heat, unlike the subway train system running periodically, vehicle fleet is usually run continuously along the road. Each one of the vehicles will generate a large amount of heat during the driving process, take a normal passenger car, for example, it generates 44W when running in a normal situation. So the total amount of heat generated by vehicular traffic is usually higher than that of the train system. In the EU, they use a segmentation system to classify each type of passenger vehicle based mainly on their size. Vehicle heat in reality are very complicated. Driving styles based on driver types are given in the following description (Zheng F, Li J, et al. [23]) :

- Aggressive, macho and unsteady
- Conservative, careful, novice
- Professional, smooth going
- Experienced, speeding

These factors are very specific ones in determine the traffic energy consumption, in this study we are not thinking about too much. Other issues such as load factors and road slope also have been studied [24]. It is around 30±12% higher than type-approval values for light-duty passenger vehicles in real world fuel consumption [25].

3.3 Field Measurement

3.3.1 Passenger Car

Field measurement has been carried out to study the temperature distribution under a passenger car and a medium truck. 2 separate test was conducted by our lab and the company related to this topic. The original purpose of this measurement was to study some parametric of the vehicle during driving, such as the engine, tire, bottom, and exhaust pipe temperature [26]. Then using these parameters to build a vehicle inter-reaction with the circumstance such as asphalt road and air inside the tunnel. However, these data are still inadequate to build a more general model due to the lack of a measured vehicle.

The first test is a passenger car test, the car model used is Nissan Bluebird 1.8L(Figure 3.6).

(a) Side view (b) Backside view

Figure 3.6: Passenger used for field measurement

This test was carried out by 2 times on 2017.09.01 and 2017.09.13. 9 button temperature sensors were attached to the car bottom because of high temperature due to engine operation. Button sensors can only measure the surface temperature is attached to, so how to let the button sensors just measure the temperature of the car bottom with less air effect as possible is very important. Calibration needs to be done before field measurement. In the wind tunnel, 5 cases were set up on an asphalt specimen which was used to conduct heat transfer tests.

Then, 9 sensors were set as the figure below (Figure 3.8,3.9).

(a) Sensors used

(b) Test cases

Figure 3.7: Wind tunnel calibration

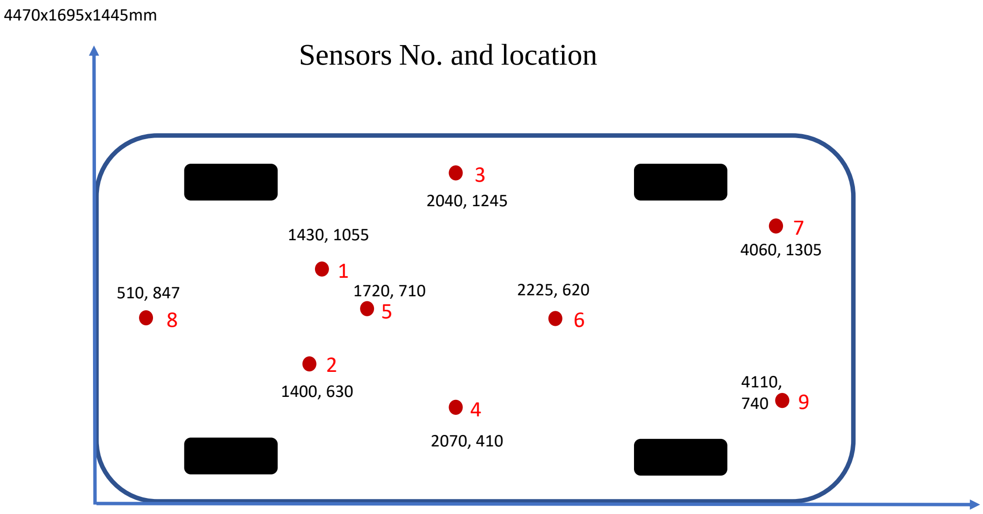


Figure 3.8: Sensor distribution at the bottom of vehicle

(a) Sensor 1

(b) Sensor 2

(c) Sensor 3

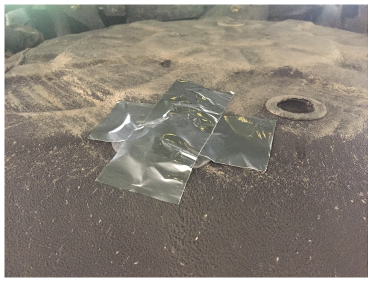
(d) Sensor 4

(e) Sensor 5

(f) Sensor 6

(g) Sensor 7

(h) Sensor 8



(i) Sensor 9

Figure 3.9: Sensors attachment at car bottom

3.3.1.1 Measured Data

Measurement has been carried out 2 cases with the same vehicle model as shown in Fig 3.10 and Fig 3.11. The test was carried out between Yokohama National Univ. and Yokohama Station. High temperature has been measured in both cases. In Fig 3.10, the blue range represents driving time, where temperature increases at the beginning of each time. The rest part is stopping time.

In Fig 3.11, sensors were applied directly on the exhaust pipe in Case2, that is why a much higher temperature was observed compared with Case1. Other parts of the car bottom are also measured with a high temperature up to 70°C.

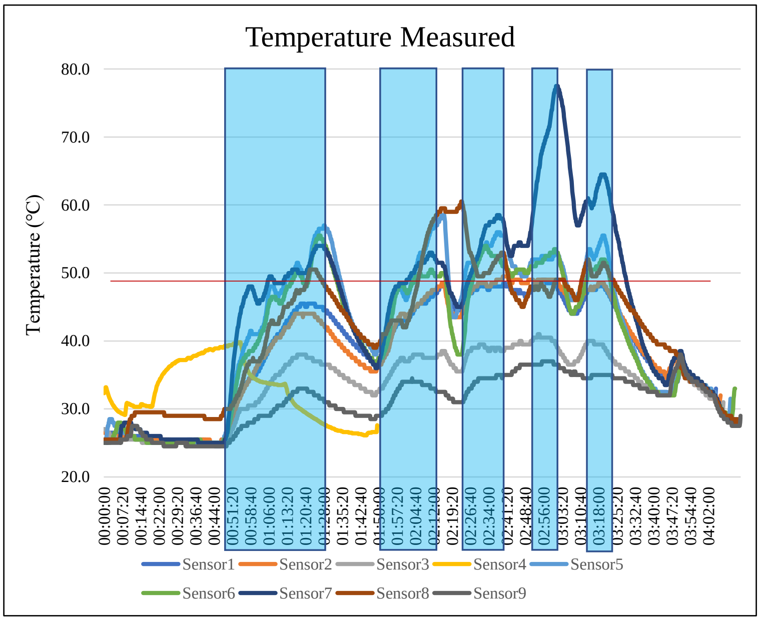


Figure 3.10: Vehicle bottom temperature distribution of Case1

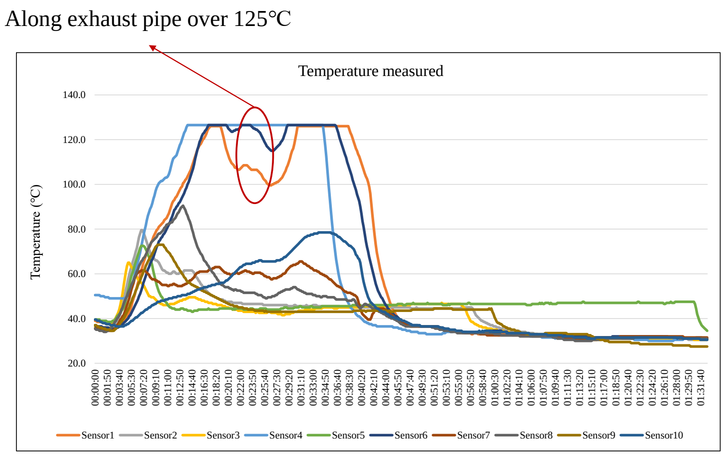


Figure 3.11: Vehicle bottom temperature distribution of Case2

3.3.2 Middle Size Truck

The other test was truck temperature measurement after 30 mins running in an open field near Ooi Junction under the support of Metropolitan Expressway Co., Ltd. This test was aimed at knowing how high will the bottom temperature could become during driving, which I suppose to using it to calculate the radio heat transfer from vehicle bottom to pavement inside tunnel. Measurement was conducted on November 6th, 2017. Again, temperature sensors were applied under the bottom of the vehicle(Fig 3.12). Also, several points were measured using the thermal camera and digital thermometer.

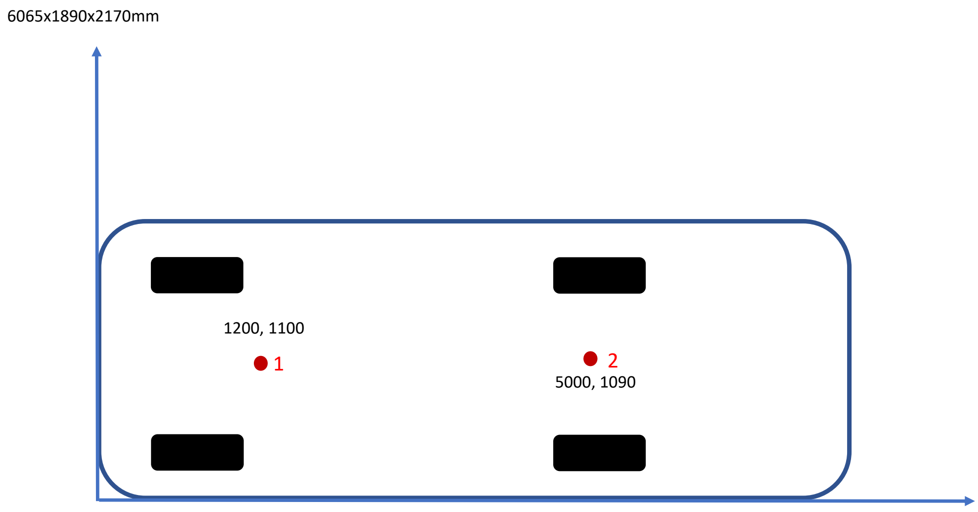


Figure 3.12: Temperature sensors under truck

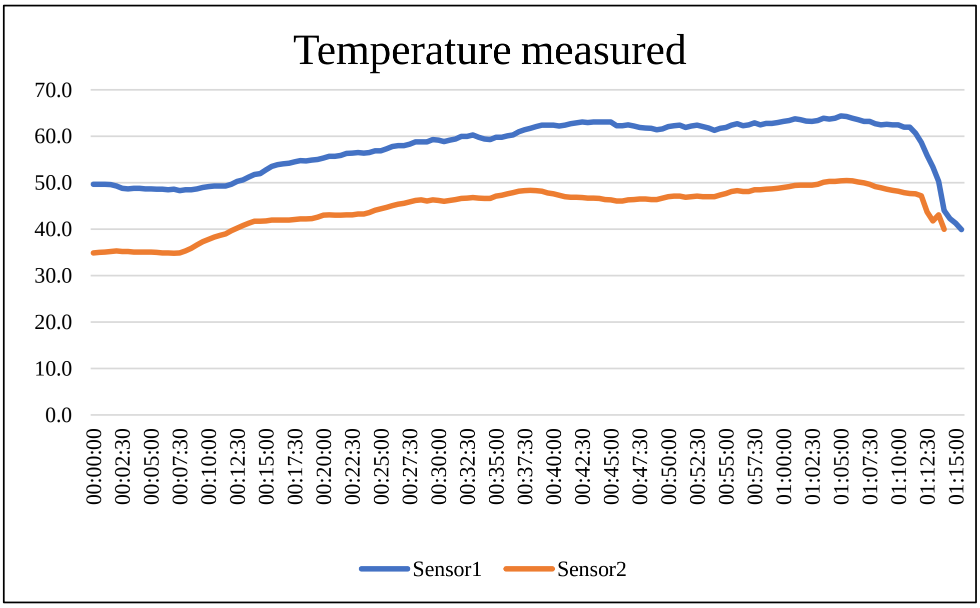
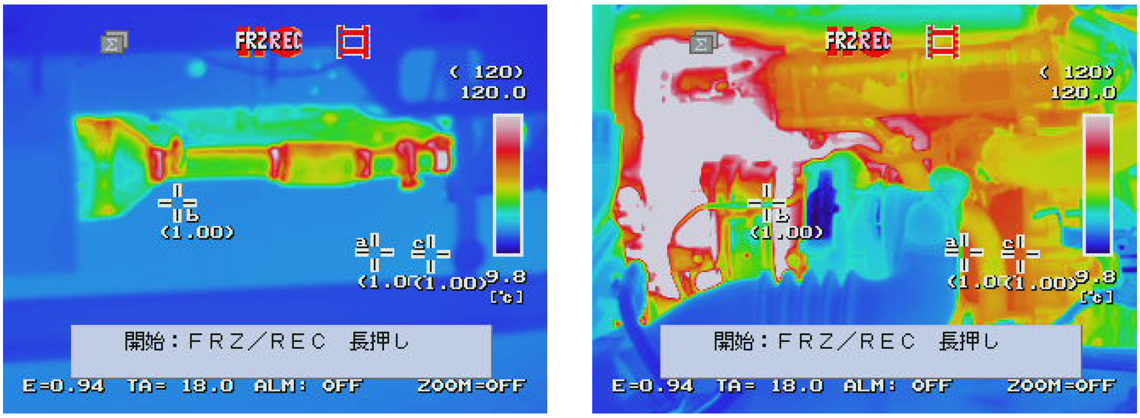


Figure 3.13: Truck temperature measured by sensors

Engine and exhaust pipe temperature were can be checked by thermal data in Fig 3.14. Pipe temperature neat the outlet was measured at around 113°C, whereas engine temperature was over the 120°C. The truck has a higher temperature around the engine probably due to its more powerful engine. Usually, it also has a larger emission amount which will affect more on the air temperature inside the tunnel.



(a) Pipe temperature (b) Engine temperature

Figure 3.14: Thermal camera figures

Chapter 4

One Dimensional Heat Transfer Model

In this chapter, we will discuss the general heat transfer model inside the tunnel under the influence of moving vehicles. In general, the temperature distribution inside the tunnel of different parts is varied. It usually increases in the traffic direction.

Moving vehicle generates airflow along the traffic direction, some researchers already study on this before [17, 27]. Chen et al conducted experiments to study airflow induced by vehicle, the results showed that mean airflow speed is about 1/3 of vehicle speed under normal traffic conditions and is weakly depend on the variation of vehicle size. Moreover, flow speed in the upper parts of the tunnel is only about 40% as it is around the vehicle. This study indicates that only a part of air mass inside the tunnel is moving under a speed close to traffic, in general, it only has 1/3 of traffic velocity. So we can treat vehicles and tunnel air separately to study heat transfer problems. Other studies such as [16, 28] were based on the trained model. One easy model to understand this is to imagine that each vehicle gives most parts of heat into the air directly or indirectly through convection with an asphalt surface and concrete wall. Heat energy will stay in the air at first, then it will travel forward with the vehicle under a slower mean speed, go out by transverse ventilation system, go through a road surface or concrete wall. As each vehicle gives out heat continuously when moving along, it can be assumed that air inside the tunnel is forced to drive forward by vehicle and also being heated when moving along. Now the problem is reduced to calculate how much heat per time per distance will be given out by vehicle. Then using the velocity data of axial air collected in a real site, we can calculate how much heat will travel forward, how much heat will be extracted by the ventilation system.

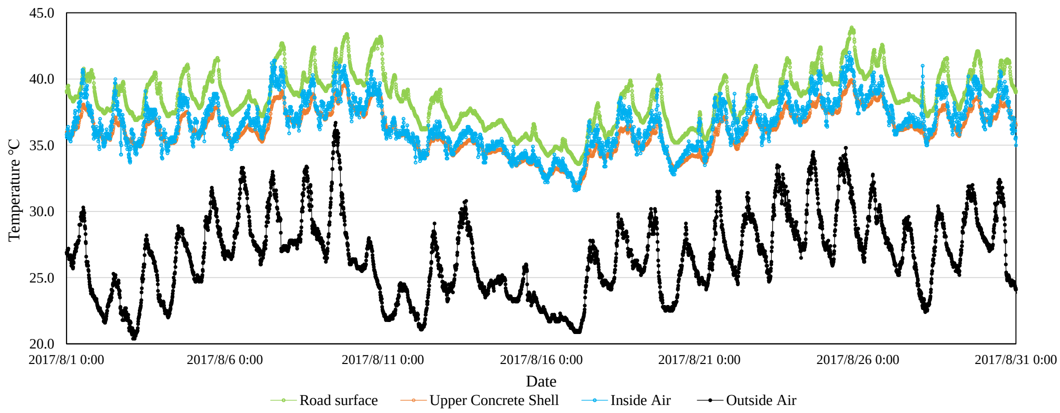


Figure 4.1: Temperature in 21.6 kp clockwise

4.1 Governing equation

A model has been made to evaluate heat transfer inside the road tunnel system, including all main possible way the heat energy can transfer. An 18.2km long with typical shield cross-section on the most range is selected as calculation objects. Moreover, moisture, traffic volume, and temperature sensors are applied on both counter-clockwise and clockwise direction in several kilo-position. Based on measurement data inside, the air relative humidity (RH) is always around 48% without large variation, it only absorbs 0.2% heat compared with air inside tunnel if they both increased 1°C, which means the latent energy of water vapor can be neglected. All physical properties used in this study are provided in Appendix tables A1 and A2. The model is made and calculated using Excel and Matlab to deal with several groups of data. All heat energy mentioned above shall be balanced as 4.1:

$$Q_{air} + Q_{wall} + Q_{vent} + Q_{road} = Q_{vehicle} \tag{4.1}$$

4.2 Heat generated by vehicle

All the energy that is released from fuel-burning finally will turn into heat. To roughly calculate the total amount of heat, traffic composition and volume are required. Unfortunately, traffic details are difficult to collect as vehicle models vary from type to type. The highway operating company only categorized into 2 types by length than any other features: those with length less than 5.5m and over 5.5m. Heat load per meter tunnel within August 2017 was calculated under the assumption of that length less than 5.5m, mainly consume gasoline 18km/L) and large vehicle (longer than 5.5m, mainly with diesel engine, consume 4km/L). These parameters were determined by referring to the data provided by MLIT Japan [29] and JASIC [30]. Heat value of gasoline and diesel is 32MJ/L and 31MJ/L respectively. So we can use equation 4.2 to calculate the traffic heat amount in August 2017.

$$Q_{vehicle} = k_{large} q_{diesel}/E_{large} + k_{passenger} q_{passenger}/E_{passenger} \tag{4.2}$$

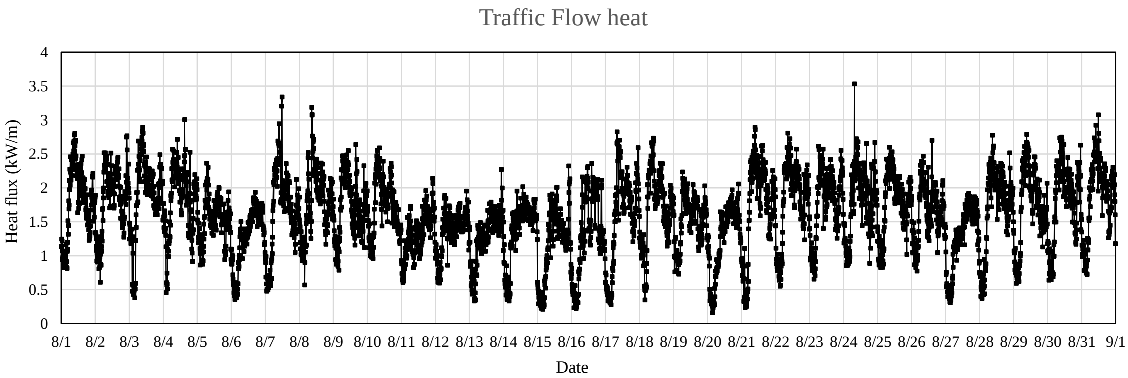


Figure 4.2: Traffic heat assumption

4.3 Axial direction heat

4.3.1 Air flow generated by vehicular traffic inside tunnel

The air flow generated by traffic will be discussed in this section. Fig 4.3 shows the direction of the airflow which is perpendicular to the tunnel cross-section and along the traffic direction.

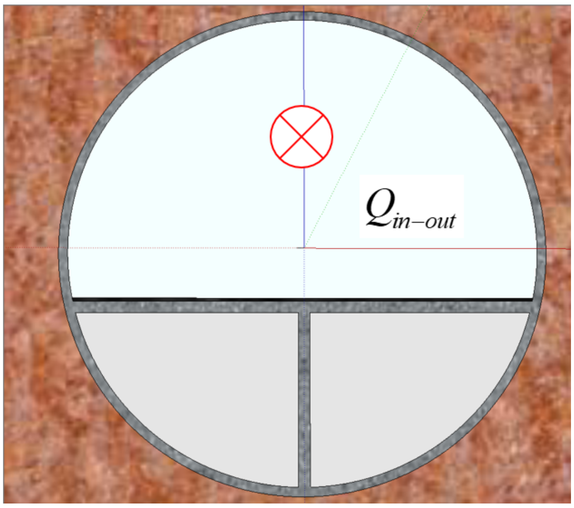


Figure 4.3: Axial heat transfer

Traffic induced flow, often known as piston effect, is very important in dealing with underground heat and mass transfer. This is a simple heat transfer model, let us take a certain range l_i in the axial direction, when cooler air (it has been observed that air temperature is increasing along the traffic direction) enters and leaves with a higher temperature. A certain amount of heat $\triangle Q$ will be dragged out during time $\triangle t$. If $\triangle t$is small enough, say 10 mins, temperature differences is treated constant between spot i and $i+1$.

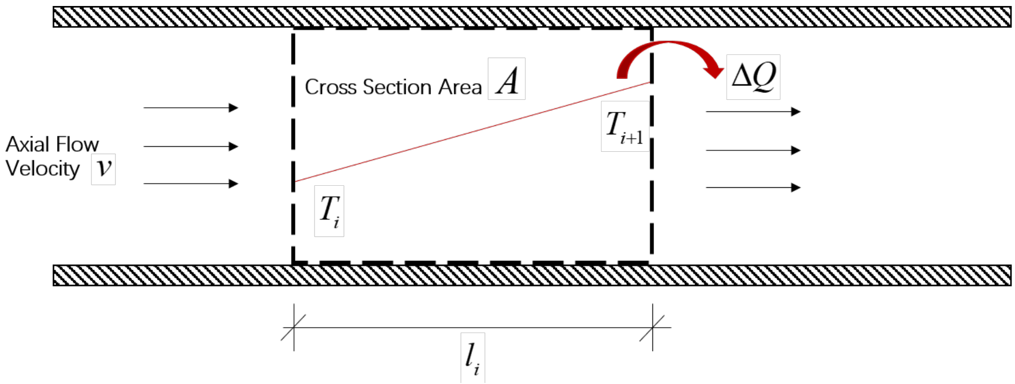


Figure 4.4: One dimension axial demonstration

4.3.2 Heat transfer due to traffic piston-effect

Heat transfer amount per meter along the tunnel can be calculated as:

$$\triangle Q_{axial} = c_{air}\rho_{air}v_{mean}A(T_{i+1} - T_i)) \triangle t/l \tag{4.3}$$

where c_{air} and ρ_{air} are specific heat capacity and density of air. l is the length of the selected tunnel section length. For piston-effect, or air mass moving induced by running vehicles inside the road tunnel. Chen et al. [27] studied the details by experimental methods. In his results, vehicular traffic speed inside the tunnel has a relationship with mean wind speed as below:

$$v_{vehicle}/v_{mean} = 3 \tag{4.4}$$

Where $v_{vehicle}$ can be known by real traffic monitors data, mean air velocity in axial direction will be calculated by simply using the relation 4.4, due to lack of field measurement data and more detailed study on relationship between mean air velocity and velocity distribution along tunnel center to wall.

Fig 4.5 was calculated based on equation 4.3. Axial heat is varied in a different position due to different boundary conditions, such as entries, exits and central ventilation at several places. Near Gotanda and Nakameguro there is a central ventilation system where outside cooler air can be extracted directly. Air temperature also drops near some exits and entries where outside air is easy to come in and affect the temperature inside the tunnel. In fig 4.5, we can also see that the right side value is smaller than the left side. This means the longitudinal ventilation system is worse than the transverse ventilation system in dealing with the temperature rising due to the reason it only brings heat forward.

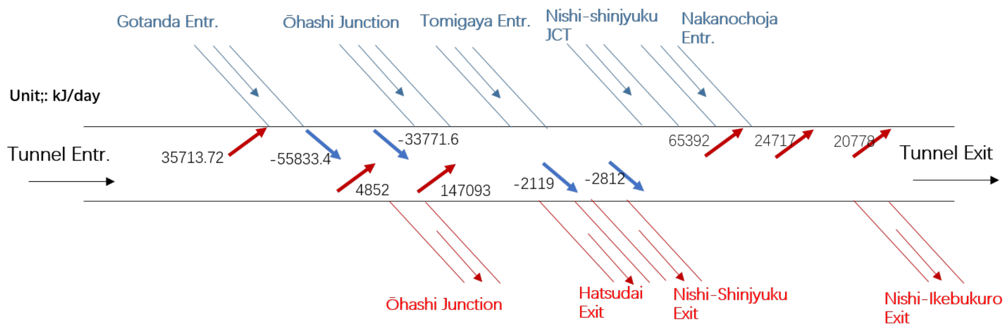


Figure 4.5: Axial heat calculated by measurement

4.4 Heat transfer at wall

When hot air moves along the tunnel, concrete wall also absorb a part of heat energy. It can be calculated using:

$$\triangle Q_{wall} = h_c \cdot C \cdot (T_i - T_{wall}) \tag{4.5}$$

In equation 4.5, C represents the circulation of shield tunnel section.T_i and T_{wall} are tunnel air temperature and wall temperature. Nusselt number can be calculated by Dittus-Boelter correlation in equation 4.6, then heat transfer coefficient h_c can be calculated by 4.7:

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \tag{4.6}$$

$$h_c = \frac{\lambda}{d} Nu \tag{4.7}$$

Where kinematic viscosity of air is chosen as $16.92 \times 10^{-6}\mathrm{m}^2/\mathrm{s}$, λ is the thermal conductivity of air, 0.0271W/m/K, Re is the Reynolds number inside tunnel. Pr is Prandtl number of air.

4.4.1 Verification using data

In real site, temperature and heat flux sensors were applied on several spots, 2 sensors in each kilo position. One on top of the inside wall at about 4m height, and the other down below at 1.6m. Each sensors collected both temperature and heat flux data at 10 mins intervals. Each sensors can measure net heat flux q_u and q_l from air into wall, where plus value means heat flux is from air to wall. Total heat absorbed by wall can then be verified using:

$$Q_{wall} = C \cdot (q_u + q_l) \cdot \triangle t/2 \tag{4.8}$$

Where C is the circumference of wall. For average amount heat in each day, we can calculate a whole month in Aug., 2017. Then take an average day amount as below. 21.6kp wall heat is 4071.39kJ/day when using equation 4.5. Compared with real site measurement calculated by equation 4.8 result 4517kJ/day, is a good match.

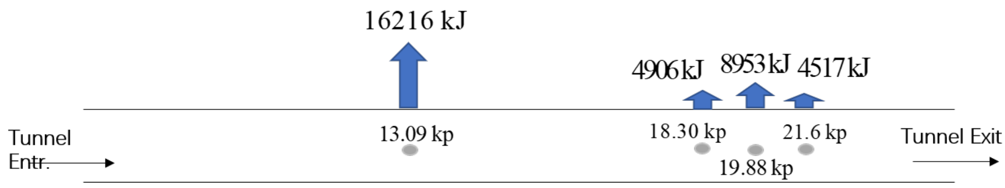


Figure 4.6: Wall heat of Aug., 2017 in clockwise direction

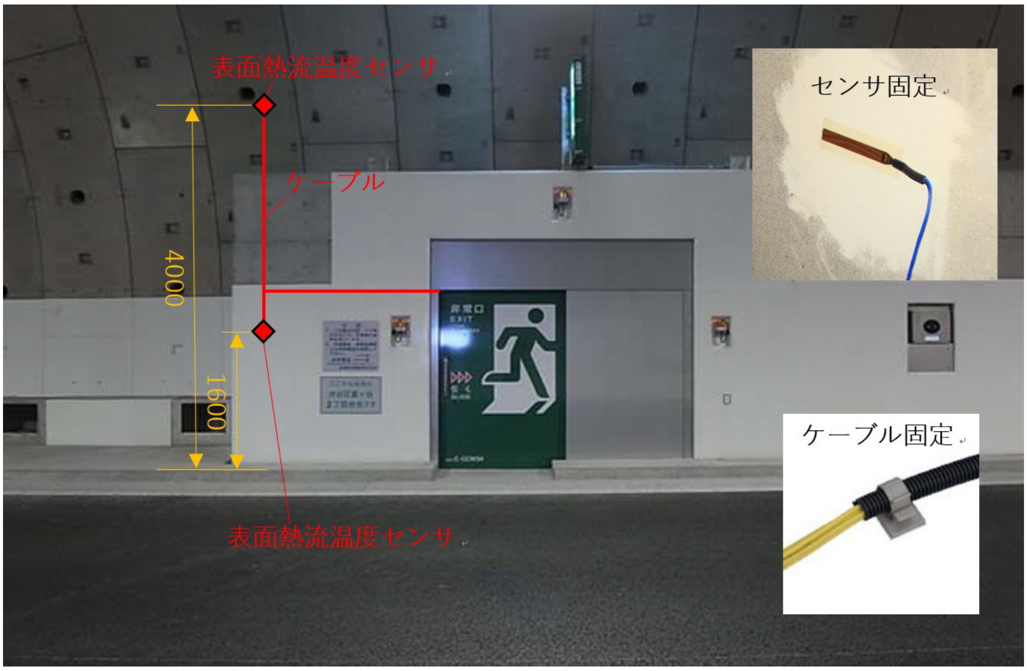


Figure 4.7: Wall temperature sensors location

Fig 4.6 is calculate by measurement data. It can be shown that the longitudinal ventilation KP wall heat is larger than transverse ventilation KP. Fig 4.8 shows the wall heat absorption in winter for both directions of the tunnel. Minus value means air is heat up by a concrete wall. Wall heat around the same location is different. Along the direction of traffic flow, wall heat changes from minus to positive as air temperature inside is increasing.

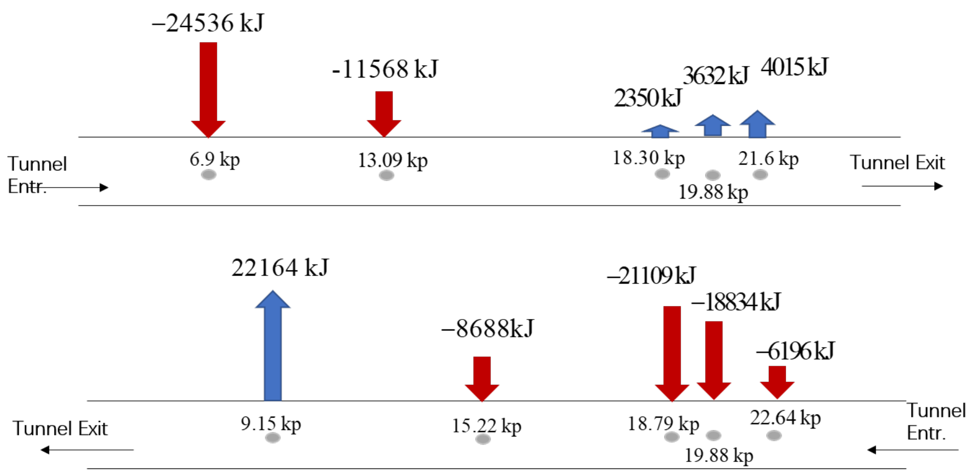


Figure 4.8: Wall heat in both direction during winter

4.4.2 Wall heat at different depth

During the daytime, the wall heat does not have a clear relationship with depth. Figure 4.9 and 4.10 show the heat amount at different KP in Counter-clockwise. MINUS means the wall absorbs heat. 9.15kp is the deepest point of tunnel that has been measured with wall heat sensors. The heat flux measured at 9.15kp in Fig. 4.10 shows that the wall always absorbs heat during day and night. This is probably due to the hotter air near tunnel exit, unknown underground water flow, which can help wall heat dissipation. However, if we look at the 18.79kp wall heat data in Figure 4.10, the amount of heat absorbed is similar to 9.15kp, despite its shallower underground position if we look at Figure 4.9. The wall heat in both the position of 9.15kp and 18.79kp can absorb as much as 1200kj/m/10mins during peak traffic time.

Besides, we only care about the high temperature at day time, if the wall can help absorb enough heat during peak time then it is good to reduce the temperature. Although the maximum average wall heat is at 9.15kp, that is because the wall always absorbs heat there, even during the night. We do not care/need so much if the wall can absorb heat at night or not, because the air temperature at night is not so high at night.

From the discussion above, we konw that whether the wall heat is effective or not is depend on how much it can absorb at daytime. The wall heat does not have a clear relationship with the depth.

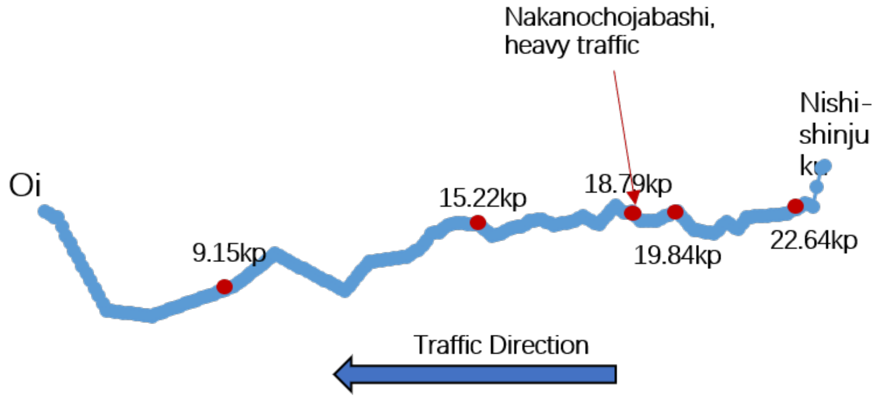


Figure 4.9: depth of each location

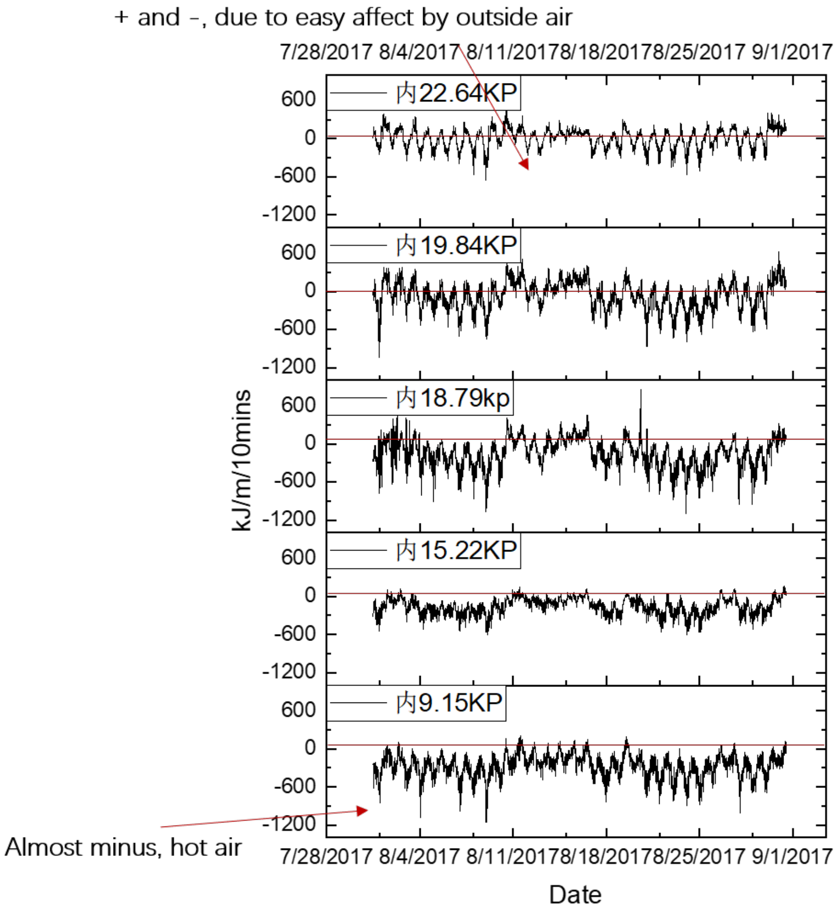


Figure 4.10: Wall heat in both direction during winter

4.5 Heat transfer into asphalt road

The road surface also absorbs some sort of energy through convection with hot exhaust air, rolling friction with vehicle tires and some parts of radiation by vehicle hot bottom [13]. These combinations were then verified by field experiments, which takes a lot of time. However in this study, roads are enclosed by an underground concrete wall, no outer factor can affect road heat except vehicle heat. Here is a simple method to calculate the average daily heat absorption.

4.5.1 Heat flux into road

The temperature changing of the road surface in different kp along the clockwise direction is shown in Fig 4.11. From tunnel entrance all the way to exit, the temperature almost always increase, although daily air temperature may change. This is a similar tendency as concrete wall temperature.

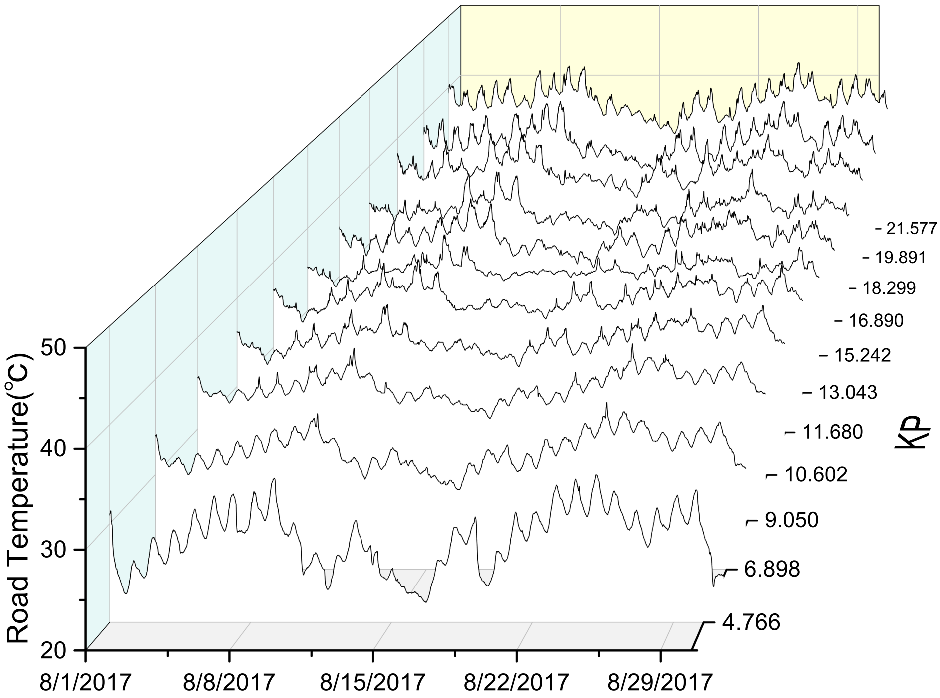


Figure 4.11: Road surface temperature in different kp

4.5.2 Heat load calculation by field measurement

In real site at 19.88kp and 21.6kp in clock-wise direction. 3 temperature sensors were applied inside the road layers at a depth of 2cm, 6cm and 8cm. These temperature sensors collected data every 10 mins. It can be seen in Fig 4.12 that upper layer temperature was higher than low parts due to direct contact with rolling tires and hot air.

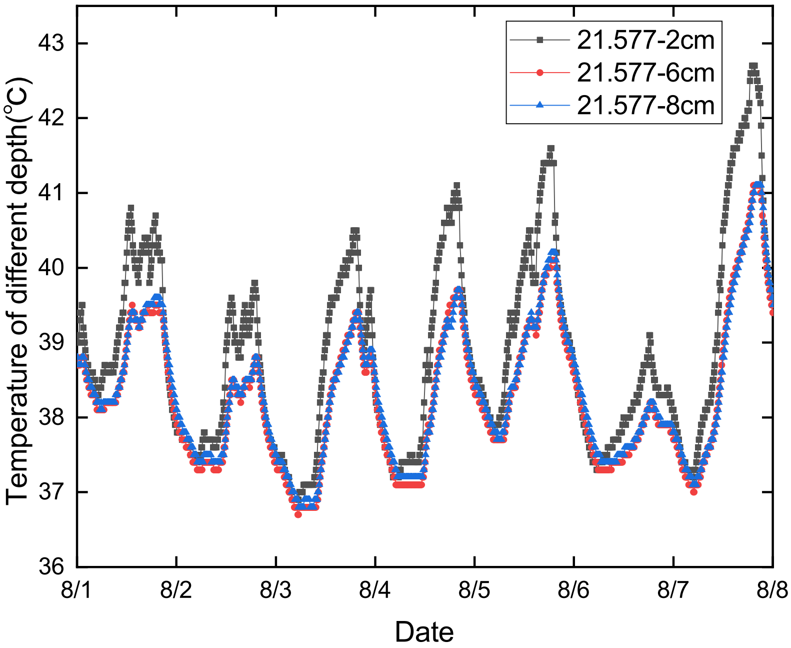


Figure 4.12: Pavement temperature of different depth at 21.577kp

If we take a short time such as 10 mins as we used before, we can simply treat the road heat is steady-state during this short time. Road heat calculation model is based on Fig 4.13, where Q_{raod} is equal the first 6cm heat absorption Q_{0-6} plus the heat flux q_{6-8} from 6cm to 8cm.

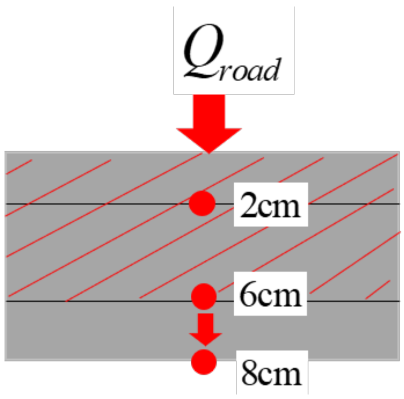


Figure 4.13: Road heat calculation model

Then we have equation:

$$\triangle Q_{road} = q_{6-8} \cdot W \cdot \triangle t + \triangle Q_{0-6} \tag{4.9}$$

Where W is the asphalt road surface width, by using first 6cm mass of asphalt m_{0-6}, heat conductivity of asphalt λ_{as}, and first 6cm asphalt temperature changes in $\triangle T_{0-6}$. We can rewrite the equation into:

$$\triangle Q_{road} = \lambda_{as} \frac{\triangle T_{6-8}}{\triangle d_{6-8}} \cdot S \cdot \triangle t + c_{as} \cdot m_{0-6} \cdot \triangle T_{0-6} \tag{4.10}$$

4.6 Heat Transfer by ventilation

2 kinds of ventilation systems were applied in Fig 4.14, Longitudinal ventilation system is on the first part until Ōhashi Junction and a little range near the tunnel exit. The rest is by the transverse ventilation system.

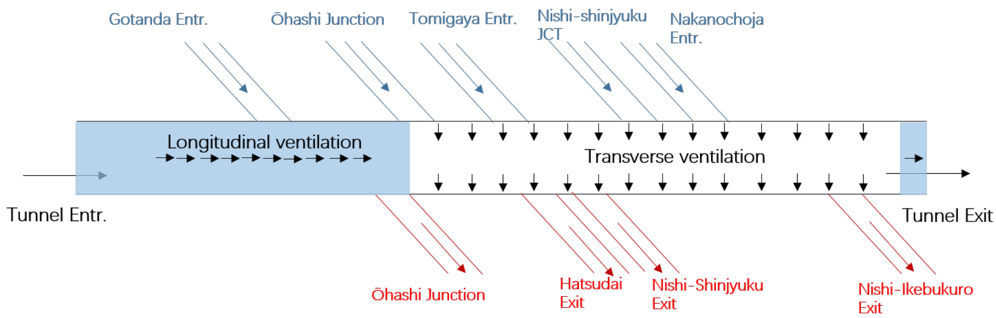


Figure 4.14: Ventilation system along clockwise direction

4.6.1 Longitudinal ventilation heat transfer

In most short tunnels, longitudinal ventilation fans were used to create more axial flow to help drag out toxic gas and pollutants. However, in this study, we focus on heat transfer inside the long tunnel under the effect of ventilation systems.

Similar to traffic direction heat transfer, longitudinal fans boost axial air movement along with piston-effect of vehicle. This type of ventilation sends airflow and heat forward, causing heat and pollutants accumulated in further spots.

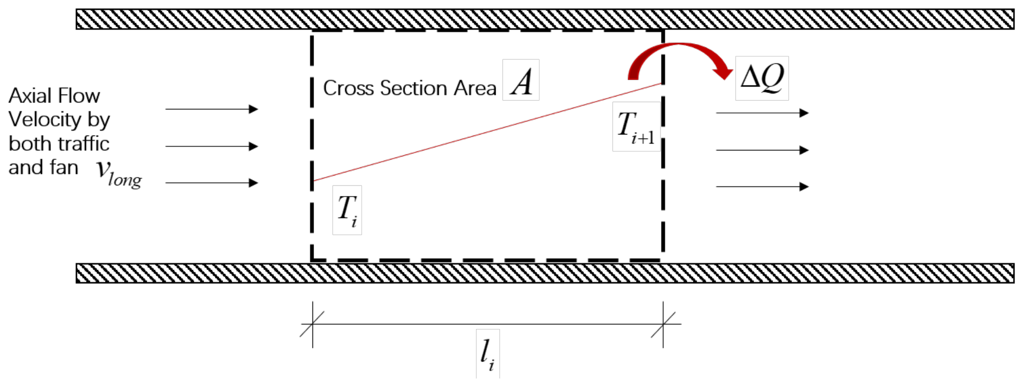


Figure 4.15: Longitudinal ventilation heat model

4.6.2 Transverse ventilation heat transfer

In the case of the transverse ventilation system range, cooler outside air is pumped in and out of the tunnel in a lateral direction through many small vents along the traffic direction. As it is observed that there is usually a temperature increase in the axial direction. So T_{i+1} is larger than T_i.

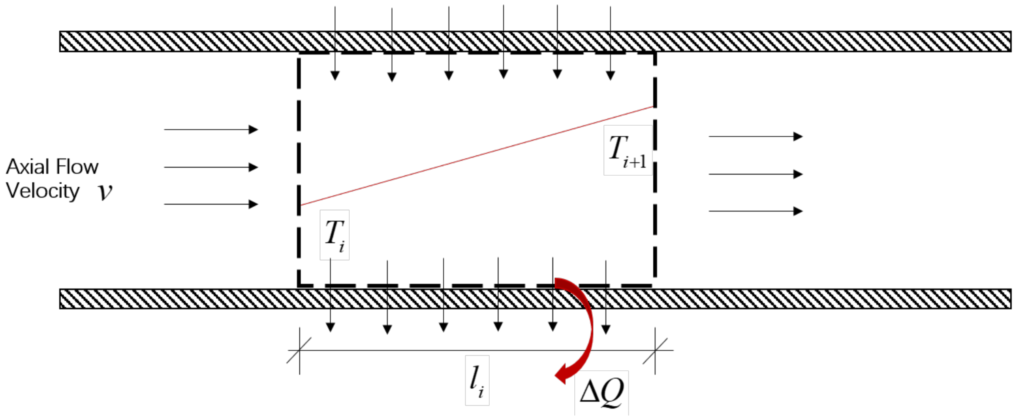


Figure 4.16: Longitudinal ventilation heat model

4.7 Tunnel Air Temperature Prediction

Now let us expand equation 4.1 with each heat load mentioned above. We can have equations as below:

$$\begin{aligned} Q_{vehicle} =& Q_{road} + h_c * C * (T_{i+1} - T_{wall}) \\ &+ c_{air}\rho_{air}V_{ventilation}(T_{i+1} - T_{outside} - T^*) \\ &+ c_{air}\rho_{air}V_{in-out}(T_{i+1} - T_i) \end{aligned} \tag{4.11}$$

All parameters in equation 4.11 can be calculated or replaced with measurement data. T_i is the input temperature at position i, which can also be determined by field measurement data. So T_{i+1}, can be calculated by equation 4.11. For the long-distance underground tunnel of Yamate Tunnel, the meaning of calculating the T_{i+1}, with a distance of l_i next to the i, is to predict the temperature of a even further distance next to position i.

Chapter 5

Validation and suggestion

5.1 Comparison with Measurement

We can choose one position at 21.6kp clockwise during Aug. 2017 to validate the heat balance model, as it is shown in Fig 5.1, black points are predicted temperature. Compared with real site temperature, it has some variances due to some random factors(sudden change of traffic fleet velocity and density in an even shorter time, axial direction wind velocity due to piston effect, lack of sensors, sensor data missing, etc.) inside the tunnel which is hard to manage. However, generally, it gives a good match to real temperature data collected at a 10mins interval. In most parts, errors are within 2°C, in nice accordance with real site measurement data.

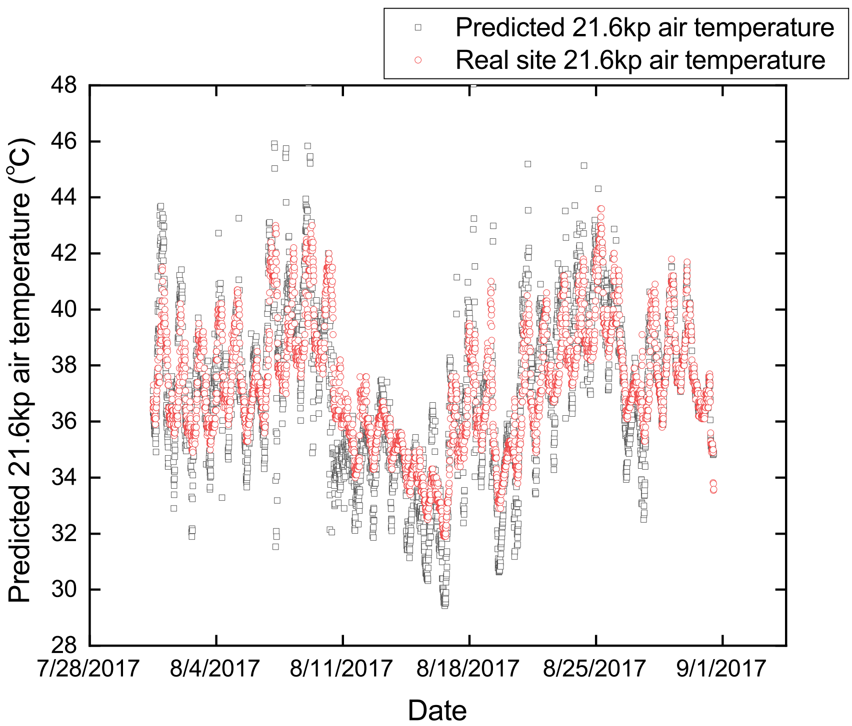


Figure 5.1: Heat balance model validation at 21.6kp

Based on the model we obtain above we can have more discussion about the details of each heat component. Fig 5.2 shows all net heat components per day in August 2017. As Vehicle can be treated as almost all heat source that causes temperature rising, it should equal to other heat sink components, in this figure, it should be equal to 50%. However as I mentioned above, this study has too many uncertainties and randomness which are impossible to give a completely accurate data. So here in this figure, it shows good results where left part vehicle heat is a heat source, almost equal to the right side 4 heat sink components.

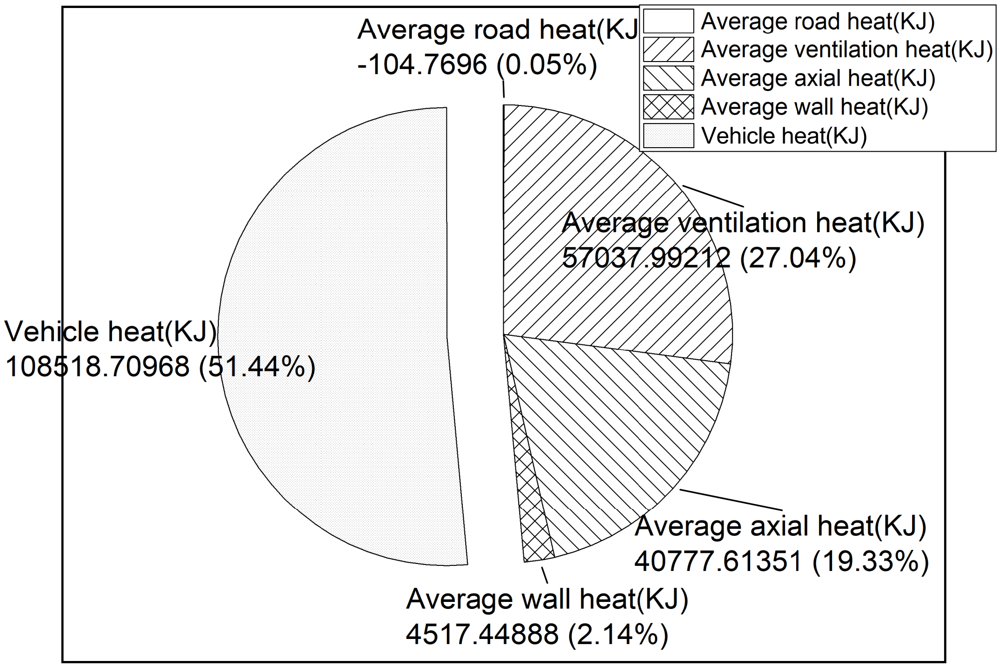
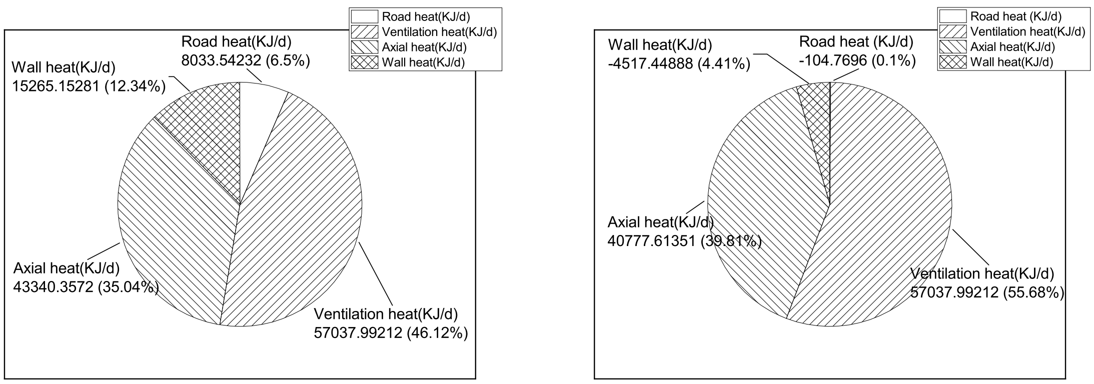


Figure 5.2: Net heat amount of each components in 21.6kp

Further more in figure 5.3, Net



(a) Absolute heat amount of each components in 21.6kp

(b) Net heat amount of each components in 21.6kp

Figure 5.3: Absolute and net heat of each components at 21.6kp

Road and wall heat absorption also varies from day time to night time when traffic volume and ambient air temperature are different. Fig 5.4 demonstrates how much heat will each heat sink absorb during different time slots averagely in Aug. 2017.

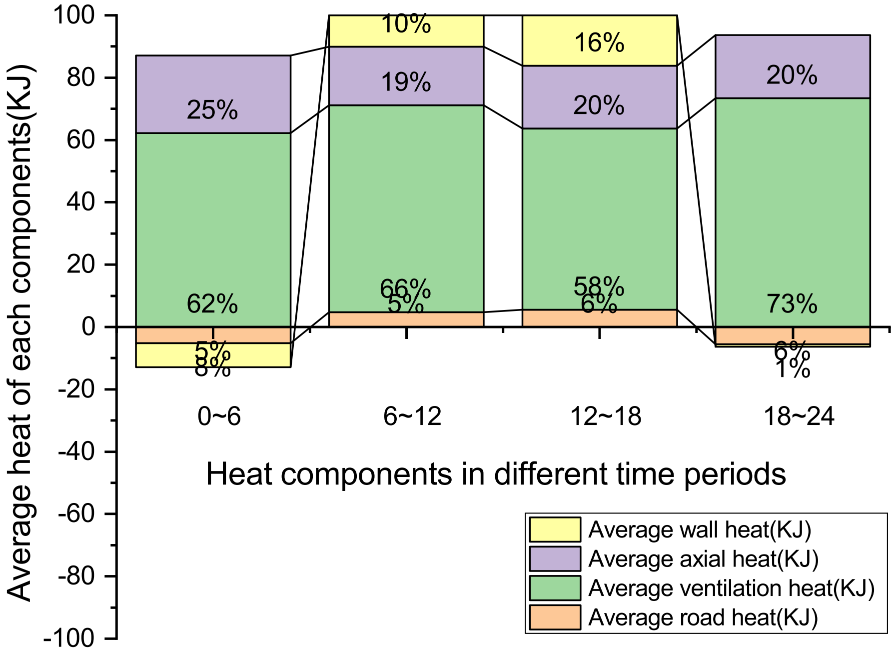


Figure 5.4: Each heat components during different time periods at 21.6kp, clockwise

5.2 Discussion

5.2.1 Road surface heat

As we can see in Fig 5.3, road pavement net heat is almost near 0%, whereas the absolute amount of heat that given out or absorbed is not that small. It consists of 7.11% of all absolute energy that transferred inside the tunnel. The reason is that during day time when traffic load and ambient air temperature are higher, road absorbs a part of heat less than 6% (Fig 5.5 and 5.6) of total vehicle heat. During the night when ambient air getting colder and traffic volume is reduced, the road surface starts to give out heat energy it absorbed during the daytime. Basically road surface can absorb some sort of heat energy, however, due to its size and is enclosed by the hot tunnel, it can not absorb enough heat energy.

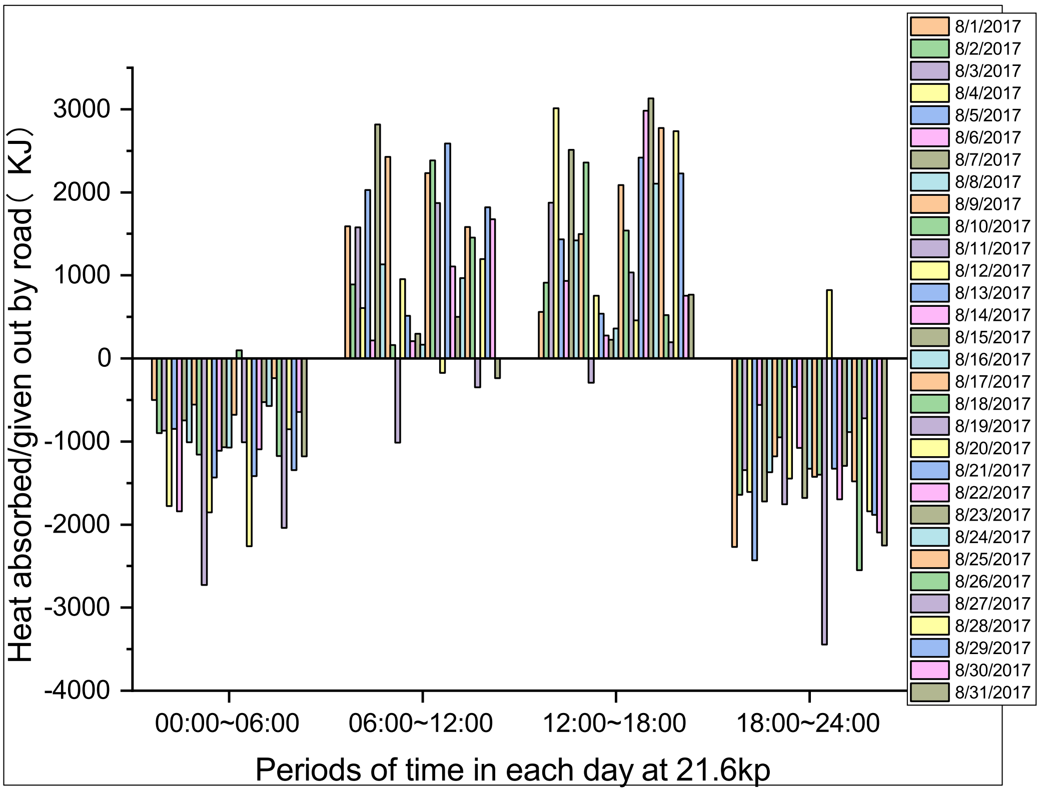


Figure 5.5: Road heat at different periods at 21.6kp, clockwise

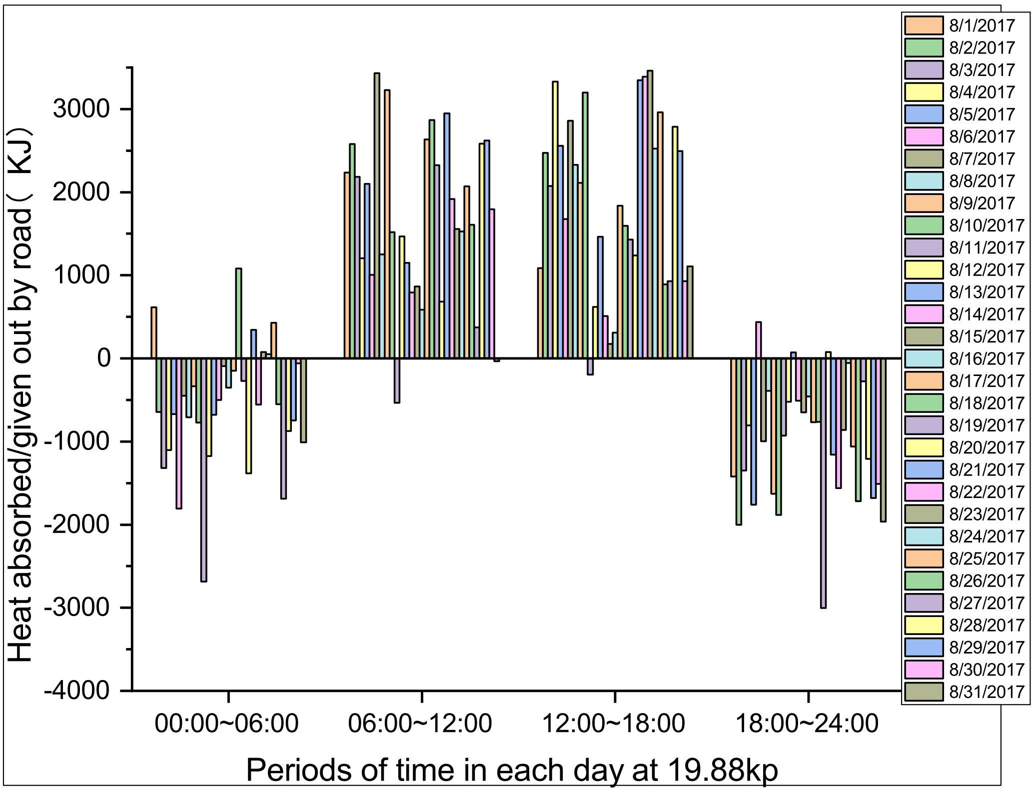


Figure 5.6: Road heat at different periods at 19.88kp, clockwise

5.2.2 Wall heat

Similar to Road pavement, a concrete wall plays the same role as a temperature buffer, absorbs heat and gives out heat during the night when the ambient air temperature drops. However, because the concrete wall of the tunnel is surrounded by the earth in a distance more than 18km, the boundary condition is much more complex to consider. In Fig 5.7 it can be seen that wall heat does have a clear shift from heat absorption to release during one day. However it still has the tendency of heat absorption during day time, and heat release at night. The amount of wall heat does not always depend on tunnel depth. The main reason is the ventilation type and air temperature that will increase wall heat absorption. Wall does not always absorb heat during the daytime. In fact, near 22.64 KP at the counter-clockwise location during August, the concrete wall gives out heat.

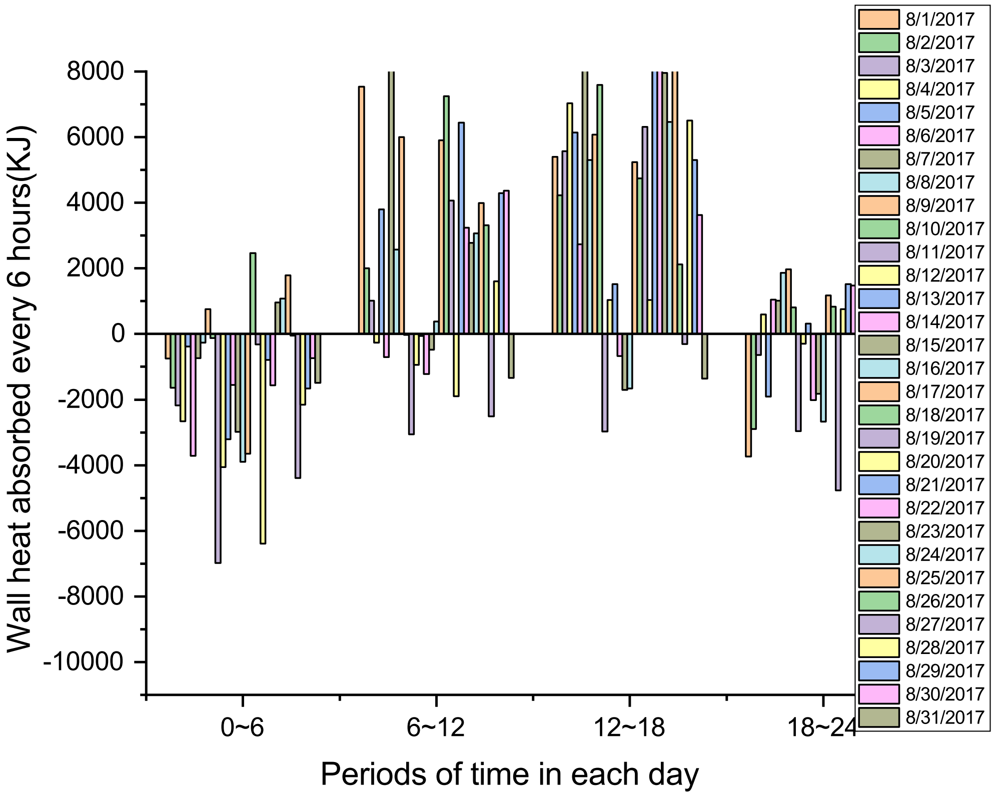


Figure 5.7: Wall heat at different periods at 21.6kp, clockwise

5.2.3 Ventilation heat

In the transverse ventilation system section, outside air is extracted into and out of the tunnel at the same time. Other extract harmful gases, it can also cool down inside air to some extent. In Fig 5.8, it shows that inside a control volume there exist 2 kinds of airflow: axial air mass flow and ventilation air mass flow. Of course, each part also carries energy when moving in and out. Ventilation mass rate is much smaller than axial mass rate over a short distance, for example over a 1m length, $\Delta m_{axial}/\Delta m_{ventilation} \approx 1814$. Which is clearly that the axial mass flow is dominant over ventilation mass flow. Even if the air outside with lower temperature is directly drawn in, it does not change the control volume temperature much, which means the T_{i+1} is only slightly larger than T_i, if the axial air temperature is increasing. In a short time, the air temperature in one spot does not change too much because of axial flow dominant the inlet air mass. This means to reduce air temperature suddenly in one spot is impossible.

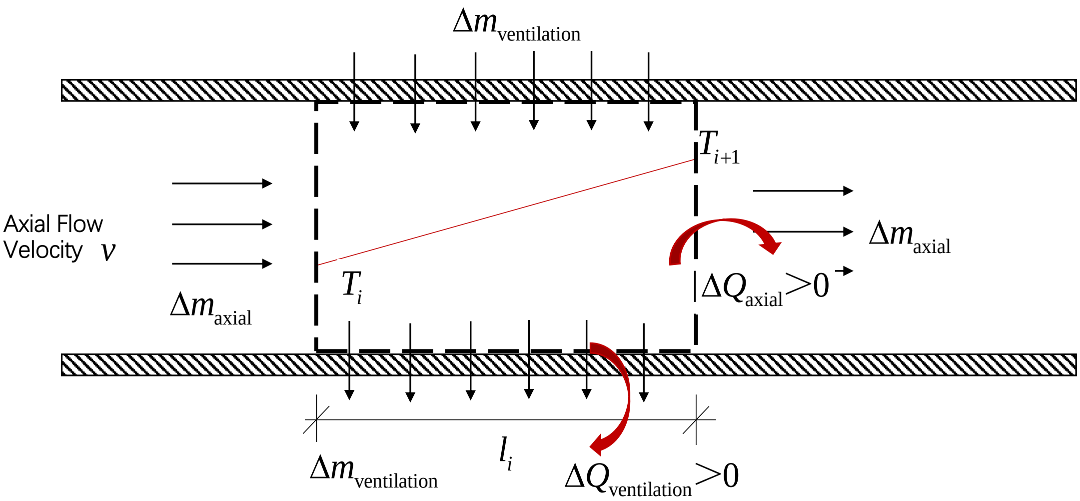


Figure 5.8: Heat and mass transfer of transverse ventilation and axial flow

However, T_{i+1}-T_i is small per 1m, 0.00068°C/m according to the heat balance model. If we assume that the temperature gradient remains stable for a 1km long, the axial temperature will increase 0.68°C. If we want to reduce the air temperature, as I already mentioned it is impossible to reduce suddenly, T_{i+1}-T_i is very difficult to change much after a short distance. All we can do is to cool down vehicle heat and change the gradient into a negative axial temperature gradient as shown in Fig 5.9.

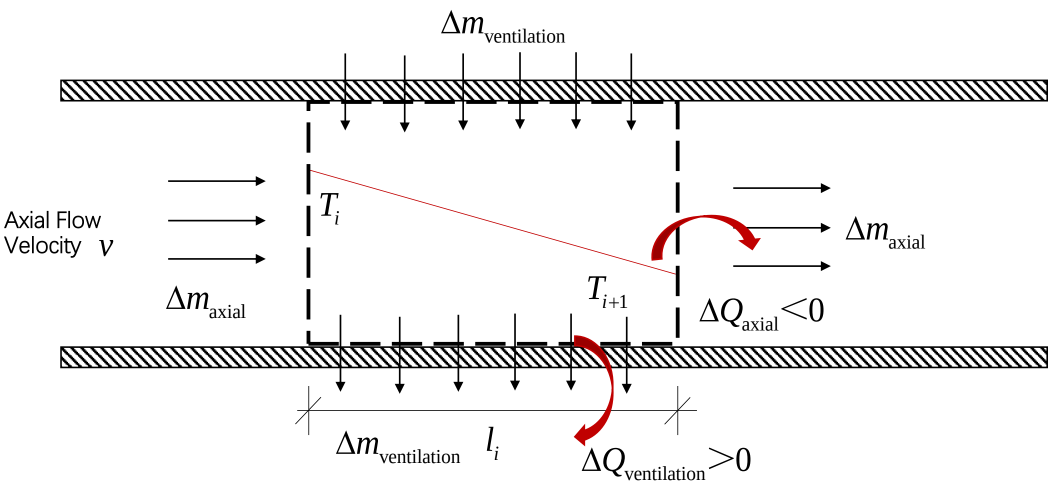


Figure 5.9: Heat and mass transfer of transverse ventilation and axial flow

5.2.4 Axial heat

Tunnel with a longitudinal ventilation system, heat and mass transfer only moves along the traffic lane. Except for some locations near the entrance or some counter axial ventilation flow. Basically, the air temperature increase along the traffic direction, due to the piston-effect that brings hotter air forward.

However, if reverse wind is formed due to ventilation fan or traffic piston-effect near entrance/exit, the axial heat may become minus due the decreasing air temperature in the traffic direction.

5.3 Suggestion

5.3.1 Cooling by underground water

Here I would like to present one possible solution, underground water cooling method. Figure 5.10 shows the attach position of underground water pipe along the traffic direction. Water need to be pumped into the pipe continuously, when the water is moving forward, the heat absorbed by the pipe can be dragged out by water pump in the plant.

Figure 5.11 demonstrate the shape of the pipe along the traffic direction. Sinusoidal-shaped plate is attached under the water pipe to absorb more heat with a larger contact surface. It can also help guiding the condensed water rivulet to the lowest point of sinusoidal plate, which makes it easy to re-collect the condensed water and do not affect the road.

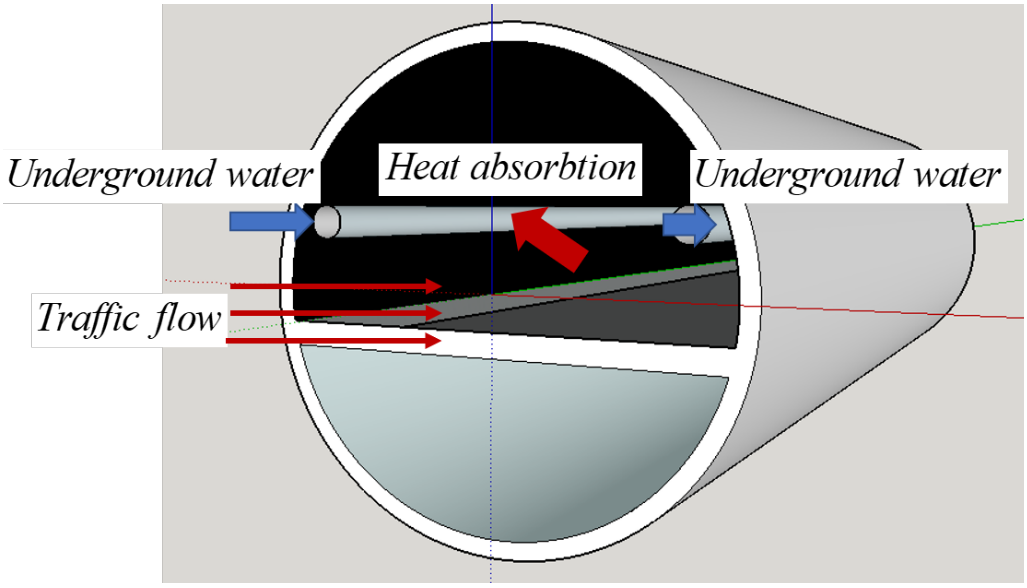


Figure 5.10: Cooling by underground water

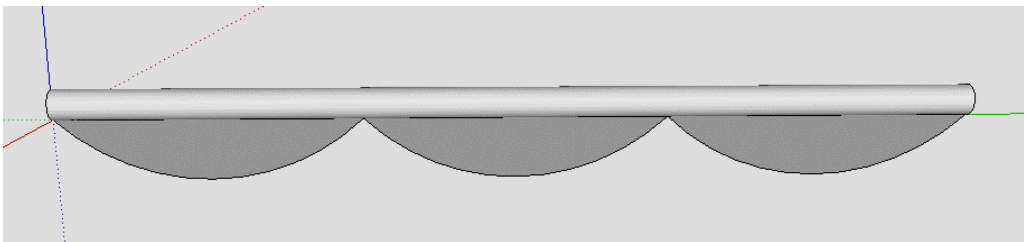


Figure 5.11: Pipes along the tunnel wall

5.3.2 Mist and ventilation combination

Mist facility has been applied to around 11km distance inside the tunnel in both directions, to reduce the temperature to some extent. For example, Fig 5.12, 5.13 shows an example of before and after a few minutes operation of mist devices on 1st, Aug. 2017. It can be seen that the air temperature at that location drops 1.5°C, which means it is effective at the beginning. About 30 mins later, the temperature rises again due to other reasons.

To study how the misting device is effective or not, we need to add mist heat absorption into our heat balance equation **??**. Again, some assumptions should be made to calculate the effectiveness of mist spray. In real site they have collected relative humidity data on many KP, of course, the operation time is controlled according to the mist temperature sensors. Mist volume and initial mist water in the pipe are also unknown.

Figure 5.12: Mist operation in tunnel

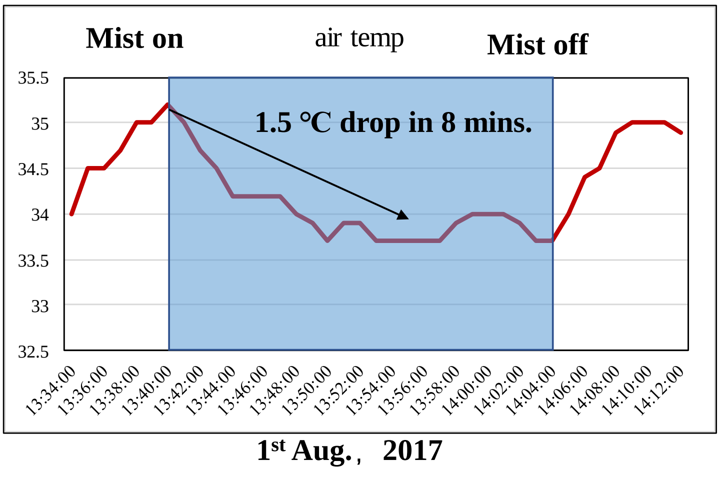


Figure 5.13: Air temperature change

Here we can assume a simple but critical case, assume that relative humidity(RH) inside the tunnel is remaining at 87%, compared to an average 47% is a very high number which is impossible in reality due to low visibility. Here we will compare with 3 different cooling methods as below:

- 1.3, 1.5, 2 and 3 times transverse ventilation volume without mist
- apply mist between 20.44kp and 21.6kp, assume humidity is 87%. Combine with both 1.3, 1.5, 2 and 3 times ventilation and mist

The results is shown in Fig 5.14, the real site temperature is

- mist with ventilation is the best way to cool down 21.6kp temperature by 5.40°C, if mist devices are applied between 20.44kp and 21.6kp and with 3 times ventilation increase.
- 1.3 times transverse ventilation volume can reduce an average temperature of only 0.72°C.
- mist alone can be able to reduce about 1.06°C at a RH of 87%.

All the methods mentioned above are ideal model analysis, take ventilation operation for instance, ventilation plants are usually on full power mode in most of summer time(Fig 5.15). We know that ventilation is the best way to reduce air temperature, the highest temperature 44°C in clockwise tunnel is still measured in 19.89kp in 9th Aug, 11:26. So regardless of electricity consumption, 1.3 times the current ventilation volume is almost technically impossible for some ventilation plant.

Mist spray and air temperature analysis is based on a critical assumption that RH inside the tunnel is 87%, which will not be in real highway tunnel due to visibility and comfort concern, etc. But compared to increase ventilation volume rate, the mist can reduce around 1°C alone under normal ventilation conditions. If it is possible to increase ventilation more, air temperature can be even cooler. But as the results show, the theoretical and ideal model can only reduce the only 5°C. Apart from its economic concern, 5°C is not a remarkable degree because the ambient air temperature is also near 35°C. It is still very hot inside even if we try these methods.

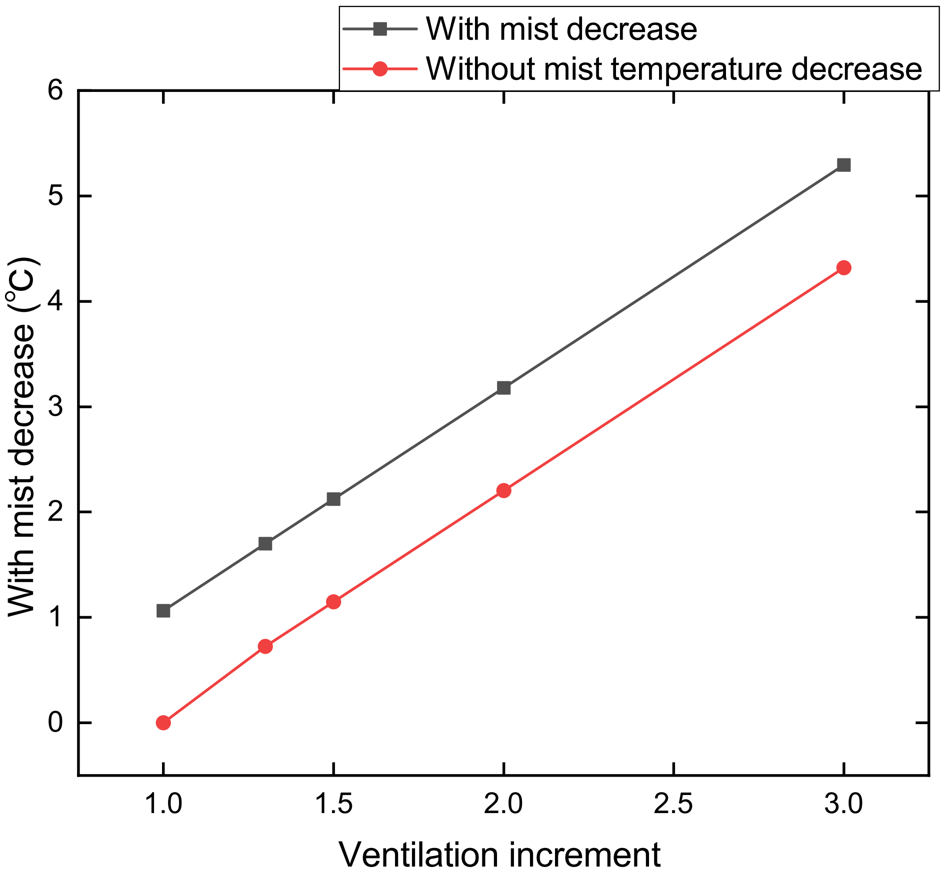


Figure 5.14: Comparison of each cooling methods

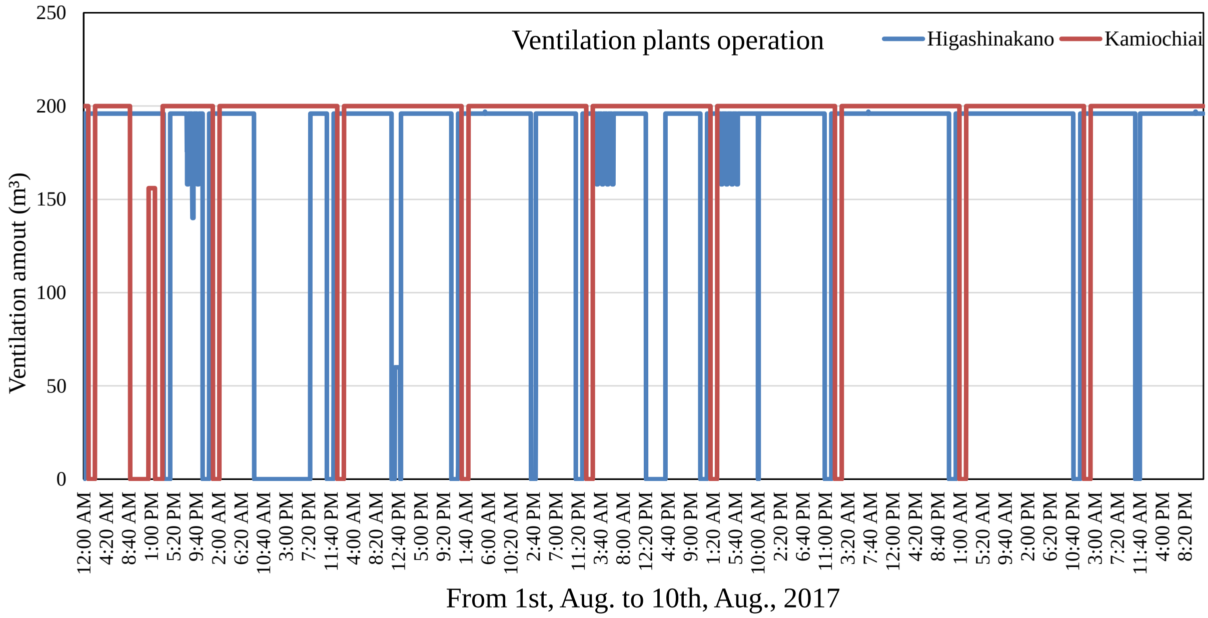


Figure 5.15: Ventilation operation in summer time

Based on current ventilation operation (Appendix A6), it is easy to figure out that Nishi-shinjuku, Honmachi, and Nakaochiai ventilation plant were not performed at there maximum power, even during daytime. And due these insufficient outside air inlet, air temperature rises between these ventilation section(in Fig. 5.16).

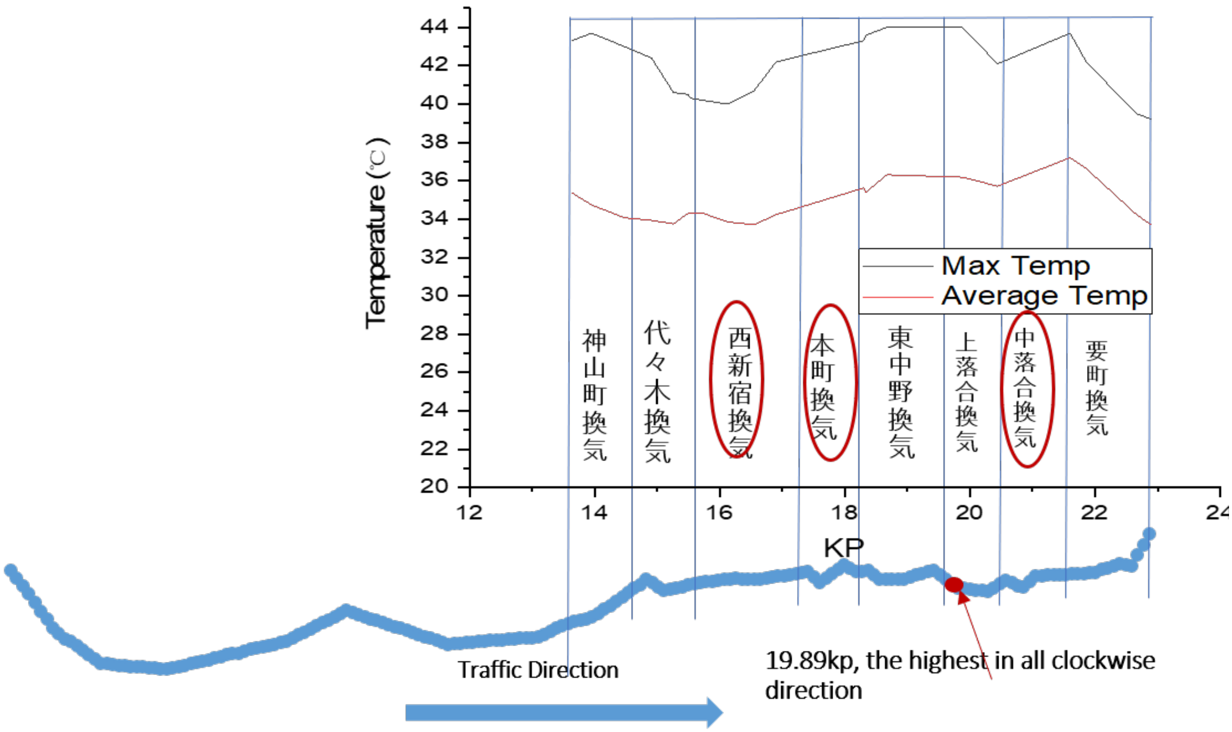


Figure 5.16: Ventilation operation in different ventilation plants

So one possible cooling method are to just set the operation power to maximum at 10: 00-20:00, because it is the hottest time in a day. For other time, current ventilation amount can be remained. In this ay, electricity fee per day will increase as shown below 5.1 (30 yen per kWh, 2000kW at maximum power in each ventilation plant).

Table 5.1: Increase of electricity fee in clockwise direction. Unit(Million JPY/day)

Nishi-Shijuku	Honmachi	Naka-Ochiai
0.6	0.75	0.519

Chapter 6

Conclusion

6.1 Introduction

The heat investigation based on measurement data in a long highway tunnel has been performed. It shows that vehicle heat is the main heat source that causes temperature rising. Most vehicle heat energy is extracted out by airflow inside the tunnel. Cooling countermeasures must concentrate on continuous air cooling methods as airflow carries most heat energy heated by running vehicle.

One reason for the extremely high temperature inside the tunnel is because many vehicles accumulated together with a short vehicular gap, this will take much more space compared with the normal condition as the air inside the tunnel will become less. Airflow along traffic direction also moving extremely slow if there are no longitudinal ventilation fans, leading to a large proportion of heat remains still. Moreover, as traffic density also increase a lot during congestion, heat generates by each vehicle does not reduce much although, under a slower speed, this will increase vehicle heat source in a certain range inside the tunnel. The concrete wall can absorb a certain amount of vehicle due to some reasons, such as depth and ventilation patterns. In the longitudinal ventilation section, hot air is moving along the traffic direction, because there is not enough colder air from outside, the temperature inside the tunnel will easily become hot. This will also enhance the heat transfer to the wall due to hotter air. concrete wall heat is not shifted from absorption to release, but in most cases, daytime absorbs more heat than night. Some parts of tunnel wall like 9.15kp, counter-clockwise always absorb heat whereas in 22.64kp, counter-clockwise, even during summer heat release to air is more than absorption.

Road heat is periodically varied from absorption in the daytime to release at night. The net heat to road pavement is very limited, however, the absolute value can not be neglected.

Transverse ventilation is the most effective method for temperature reducing, around 50% to 70% of vehicle heat is extracted through a ventilation shaft. But not very effective to reduce temperature dramatically either due to the large thermal inertia of axial direction airflow. Longitudinal ventilation and traffic-induced axial flow are similar, both are not good enough to reduce temperature directly, it just carries more heat energy forward, only causing hot air shifts in the direction of axial flow.

The mist itself is not so effective in reducing temperature, only around 1°C at a very high RH rate. In the real site, this method becomes more limited due to feasibility and safety issues.

6.2 Cooling methods

The model shows a good match with measurement data. Mist and ventilation combination is the most effective methods to sustain temperature rising, also it is the most reasonable way to deal with this problem. In real sites, ventilation and mist should work at the same pace. Further study should be conducted to see how these 2 methods affect each other. To find out how to adjust ventilation volume and mist time needs more field measurement data and analysis.

My suggestion is to increase the volume of ventilation at the range of 15.6kp all the way to 18.5kp as much as possible. This will result in the temperature reduce at 19.88kp for several degrees, although still may not be enough to solve the problems as expected. This will cost around 2 million JPY per day due to additional electricity demand. Further practical ventilation control still need to be adjusted with real operation of ventilation plants.

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Appendix

Table A1: Physical Properties

Air Density	ρ_{air}	1.127	kg/m^3	
Calculation time step	$\triangle t$	10	mins	
Specific Heat of Air	c_{air}	1.005	kJ/kg·K	
Prandtl Number of Air	Pr	0.7		
Thermal Conductivity of Air	λ_{air}	2.710×10^{-2}	W/m·K	at 1 bar (1×10^5 Pa) and 323.15K
Kinematic Viscosity of Air	ν_{air}	16.92×10^{-6}	m^2/s	at 1 bar (1×10^5 Pa) and 323.15K
Asphalt specific heat	c_{as}	0.92	kJ/kg·K	
Asphalt density	ρ_{as}	2.36×10^3	kg/m^3	
Asphalt heat conductivity	λ_{as}	0.89	W/m·K	
Asphalt pavement thickness	d_{as}	0.08	m	
Road width	W	7.0	m	
Radius of tunnel	R	5.55	m	
Circumference of tunnel	C	23.25	m	
Cross section area of tunnel	S	63.3	m^2	
Heat value of gasoline	$H_{gasoline}$	33.7	MJ/L	
Heat value of diesel	H_{diesel}	36.9	MJ/L	
Fuel consumption rate of large vehicle	E_{large}	4.5	km/L	
Fuel consumption rate of small vehicle	$E_{passenger}$	18	km/L	

Table A2: Physical Properties

Calculation length of tunnel	l_i	
Temperature of inlet in axial tunnel	T_i	
Temperature of outlet in axial tunnel	T_{i+1}	
Vehicle heat	$Q_{vehicle}$	
Road heat	Q_{road}	
ventilation heat	$Q_{ventilation}$	
Axial heat induced by traffic	Q_{axial}	
Wall heat	Q_{wall}	
Temperature between inlet and outside air	T^*	
Temperature of outside air	$T_{outside}$	
Traffic density	k	number of vehicle/km
Mean air velocity in axial direction	v_{mean}	
Traffic velociy	$v_{vehicle}$	
Heat flux from 6cm to 8cm in asphalt	q_{6-8}	
Heat absorbed by first 6cm of asphalt	Q_{0-6}	
Temperature changes in every $\triangle t$ in asphalt first 6cm	$\triangle T_{as}$	
Tunnel wall temperature	T_{wall}	
Mass of first 6cm of asphalt road	m_{0-6}	
Reynolds number of tunnel air	Re	
Heat transfer coefficient between air and wall	h_c	

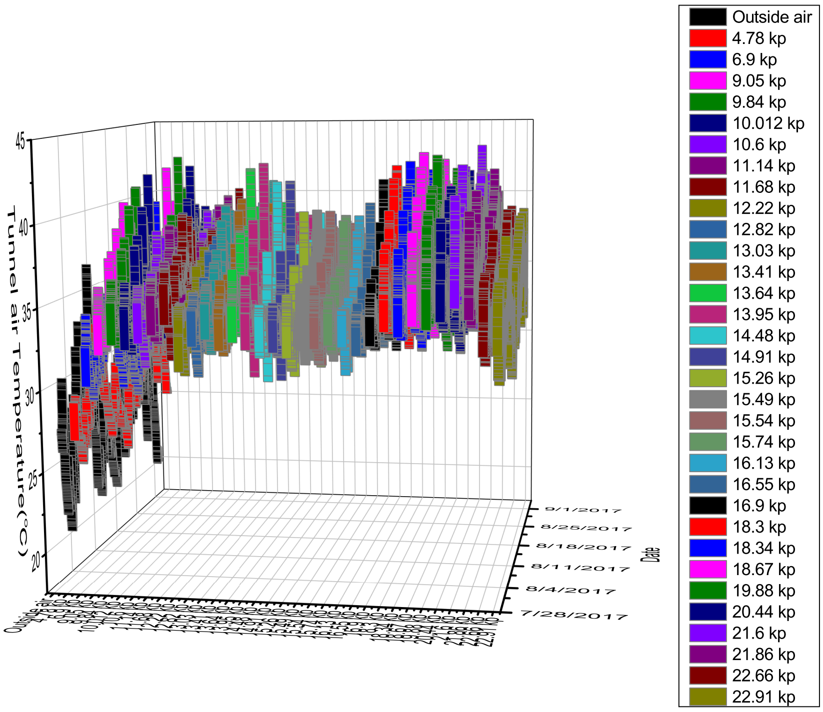

Figure A1: Temperature distribution along clockwise direction i

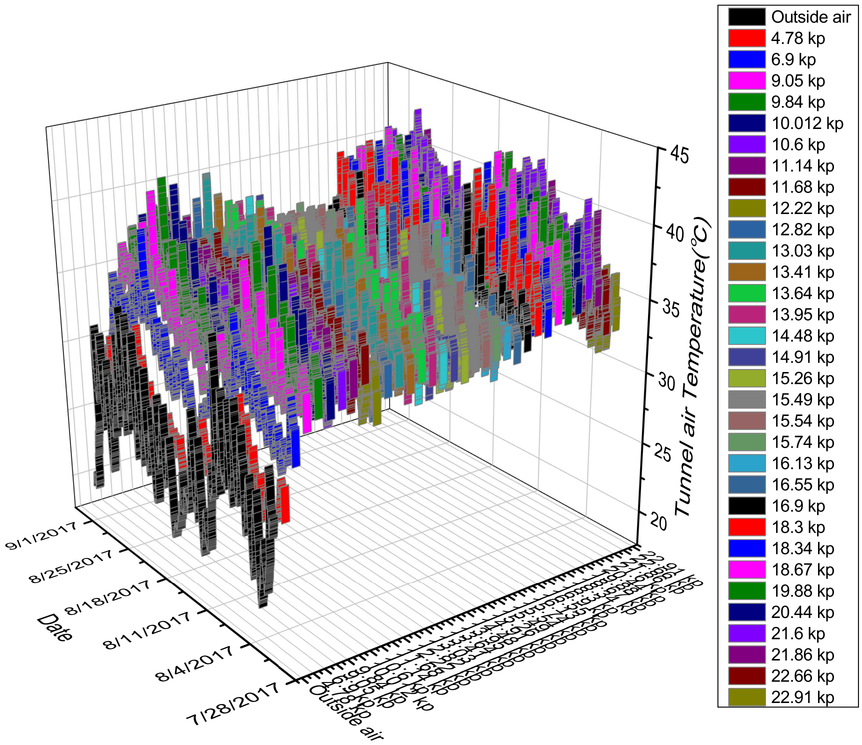

Figure A2: Temperature distribution along clockwise direction ii

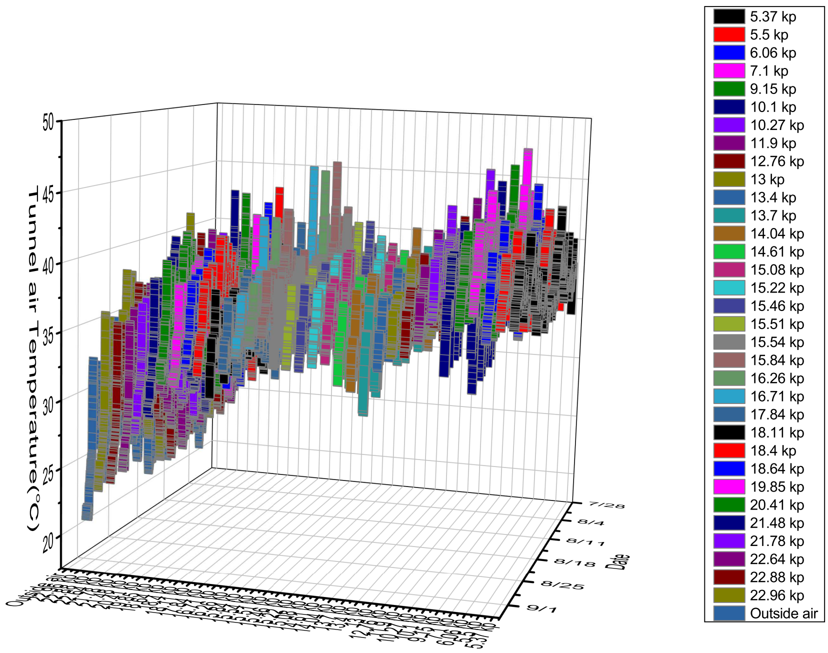

Figure A3: Temperature distribution along counter-clockwise direction i

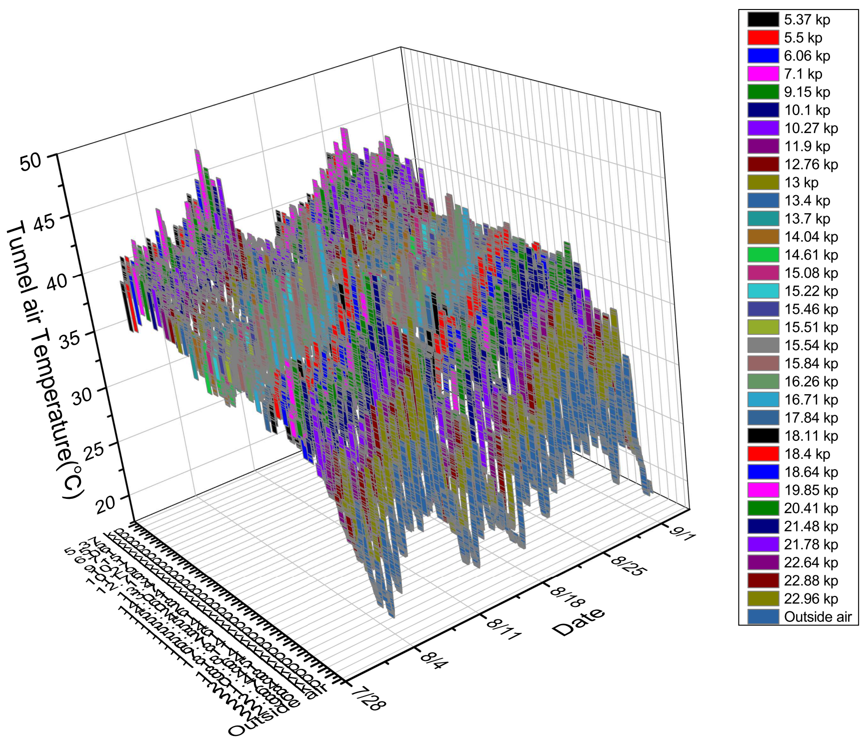

Figure A4: Temperature distribution along counter-clockwise direction ii

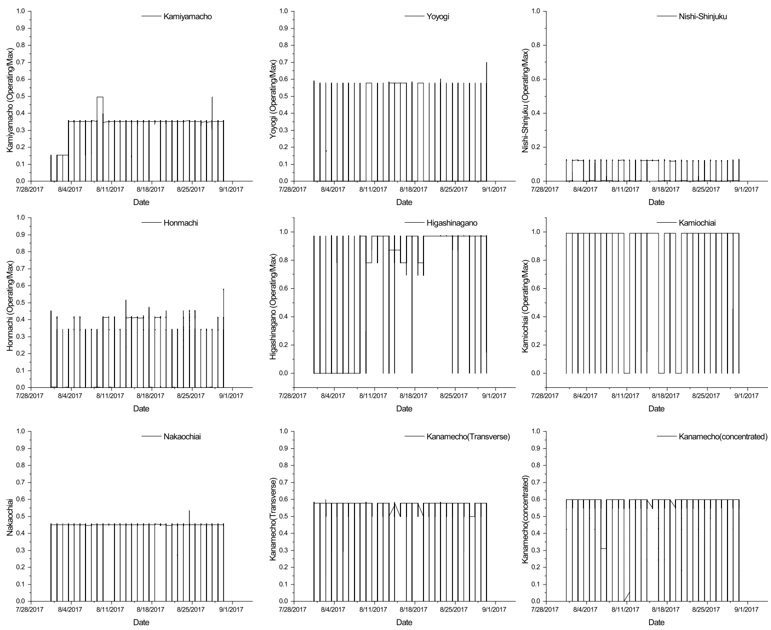

Figure A5: Transverse ventilation operation in clockwise direction i

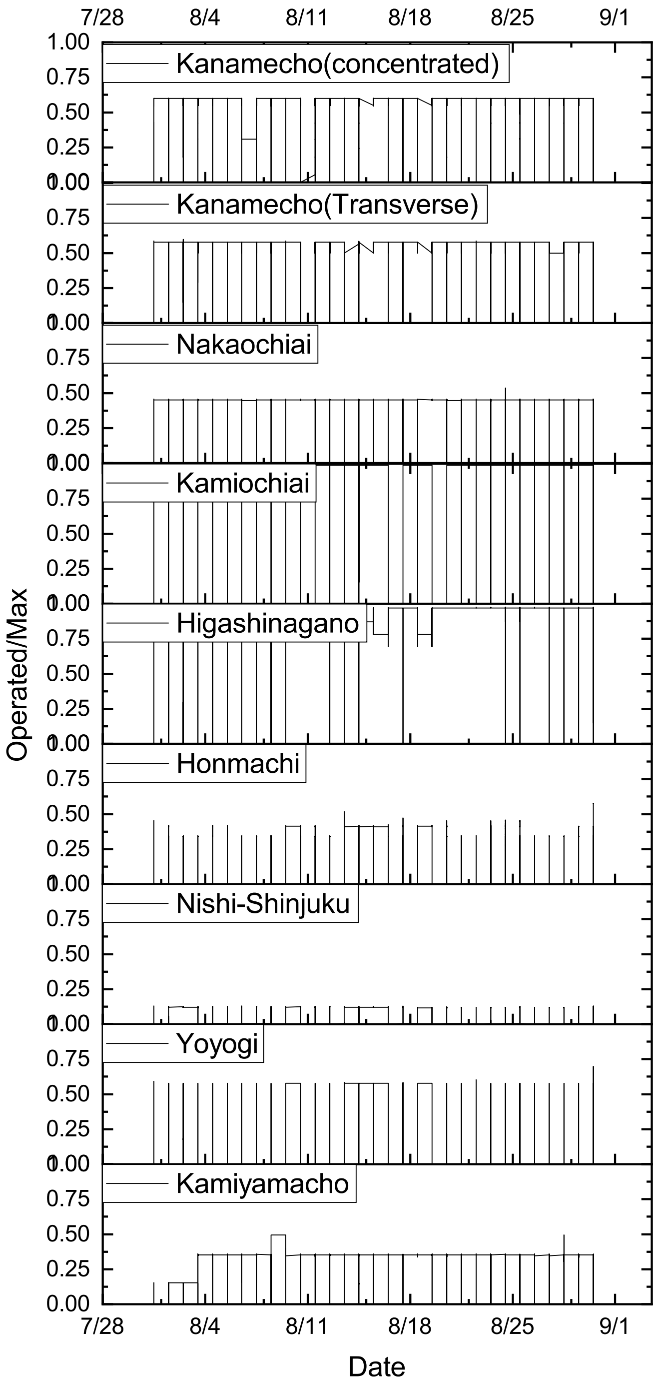

Figure A6: Transverse ventilation operation in clockwise direction ii

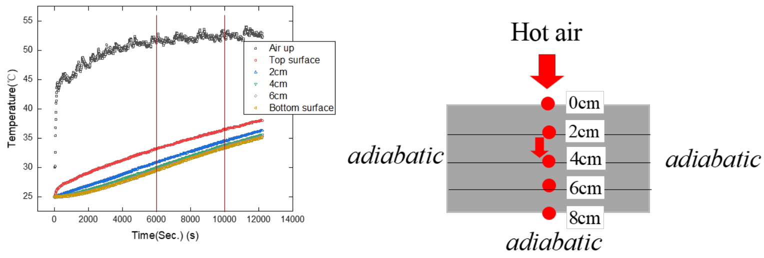

Figure A7: Calculation of road heat

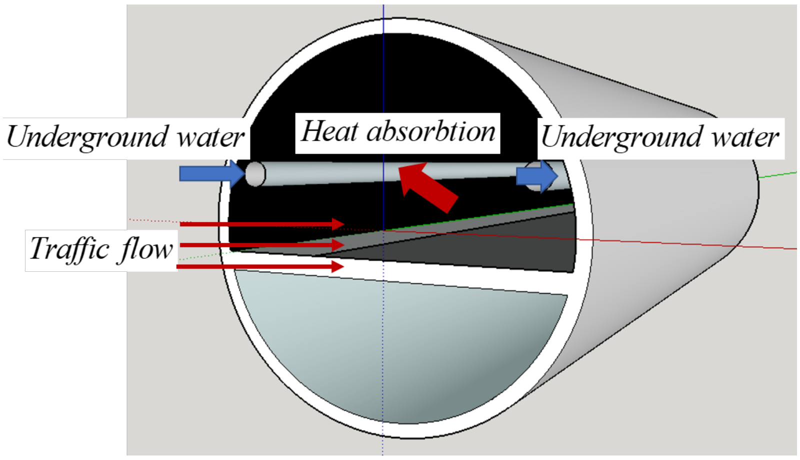

Figure A8: Possible cooling method by using underground water

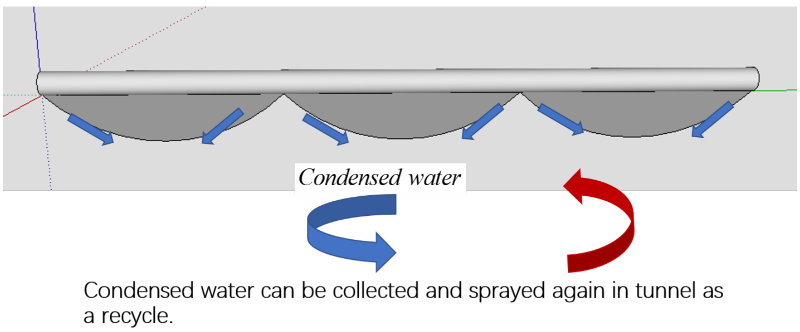

Figure A9: Details of water pipe

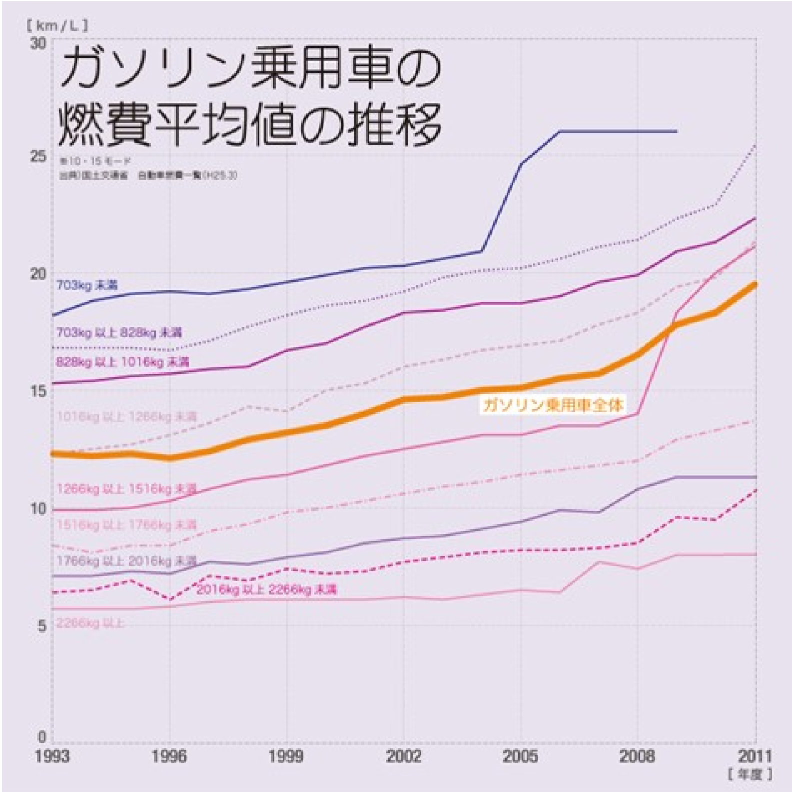

Figure A10: Heat consumption of vehicle. Source: `https://www.jccca.org/chart/chart05_01.html`

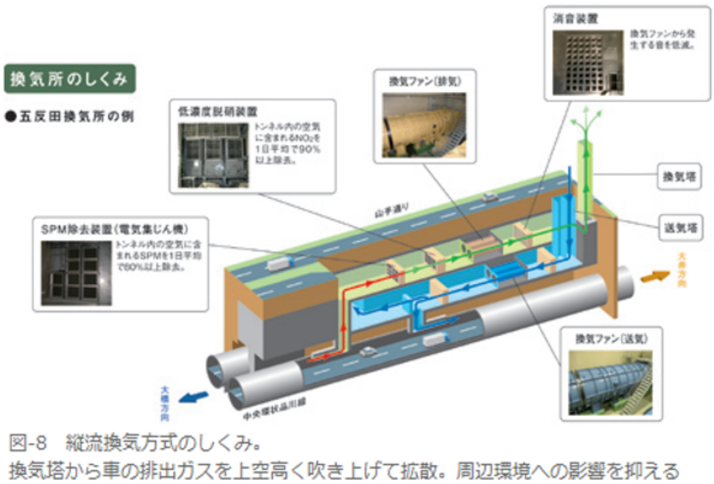

Figure A11: Operation of longitudinal ventilation system. Source: `http://www.kensetsu-plaza.com/kiji/post/6367`

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