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Heat Transfer inside a Highway Tunnel under Vehicle Thermal Effect

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Abstract **-** A highway tunnel in Tokyo experiences high inside temperature, especially during summer season. Vehicle heat was roughly calculated based on fuel consumption of different vehicle under observed traffic volume. 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**:** Road Tunnel, Vehicle Heat, Ventilation, Concrete Wall, Heat Balance.

1. Introduction

A road tunnel in Tokyo is too hot inside during summer, the highest air temperature can be up to 48.3℃ at midday, which is obviously over normal level for motorcyclist and sometimes even hard for vehicle air condition to operate normally. Generally, in case of 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 exit. Therefore, pollutant extraction is mainly focused on to ensure air quality inside. However, for long tunnel with high traffic in hot season, especially during congestion time, temperature rising issue cannot be ignored. Actually, because of bad heat dissipation inside tunnel, temperature increase along tunnel axial direction along with traffic induced wind. In previous research [1, 2], 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 afterwards.

In this study, more complicated road traffic heat is studied. Temperature distribution of road surface and concrete wall inside are measured in several spots along tunnel, traffic volume and ventilation operation details are also collected. 2 types of vehicle, representing general types on road, are measured by field test: medium truck [3], passenger car [4]. These results are used to build a heat-balance model [5], and verified using real measurement data. Finally, cooling measure is discussed based on the model.

2. Heat Transfer Model inside the Tunnel

A model has been made to evaluate heat transfer inside the road tunnel system, including all main possible way the heat energy can transfer. A 1690m long with typical shield cross-section range is selected as calculation objects, moisture, traffic volume and temperature sensors are applied on both side. 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℃, which means the latent energy of water vapor can be neglected. All physical properties used in this study are provided in table 1.

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

$$Q_{air} + Q_{road} + Q_{wall} + Q_{ventilation} + Q_{outlet} = Q_{vehicle} \tag{1}$$

In Fig. 1, vehicle generated heat and other parts are demonstrated. Inlet is on 19.89kp (km position), and outlet on 21.58kp. Traffic direction wind velocity is induced by traffic flow.

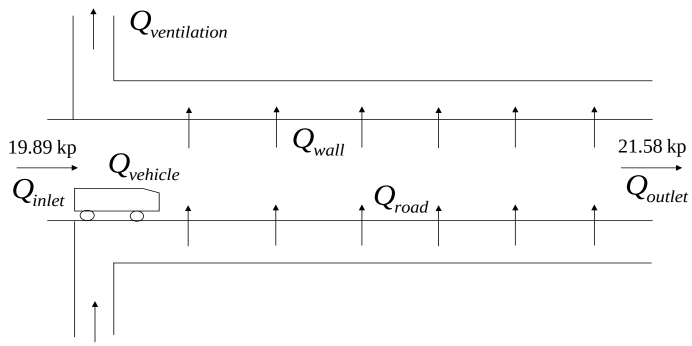

Fig. 1: Model of heat load in tunnel.

2.1. Vehicle Generated Heat

As previously mentioned, the thermal effects of vehicles are originally from fuel combustion, which varies significantly due to many random factors. The vehicle heat is the mainly cause for high temperature, in fact when vehicle runs in tunnel, the burning of fossil fuel generates a huge amount of energy which is extremely hard to quantify both in time and special domain (along driving direction) as too many random factors exist there, such as driving behaviour, road gradient [6], vehicle types [7], traffic flow velocity, air-condition in vehicle, etc. However, most (around 60%) of total energy [8] goes to air inside tunnel directly as hot exhaust gas around 260℃ [9], the temperature of exhaust pipe can also reach at 210°C. The rest (around 40%) becomes mechanical energy [10] which finally also converts into heat due to friction loss, aerodynamic drag, vehicle internal friction, etc.

Here we don't focus on calculate the details about each parts of vehicle energy consumption, the total heat given out by traffic flow is calculated based on fuel consumption for small and medium vehicle (length less than 5.5m, mainly consume gasoline 12km/L) and large vehicle (longer than 5.5m, mainly with diesel engine, consume 5km/L). Assume that during congestion fossil fuel consumes 3 times than normal speed when running on same distance. Heat value of gasoline and diesel are 32MJ/L and 39MJ/L. Heat absorption by vehicle is neglected. Data analysis based on these assumptions is conducted to predict a time-averaged heat flux given out by traffic flow as shown in Fig. 2.

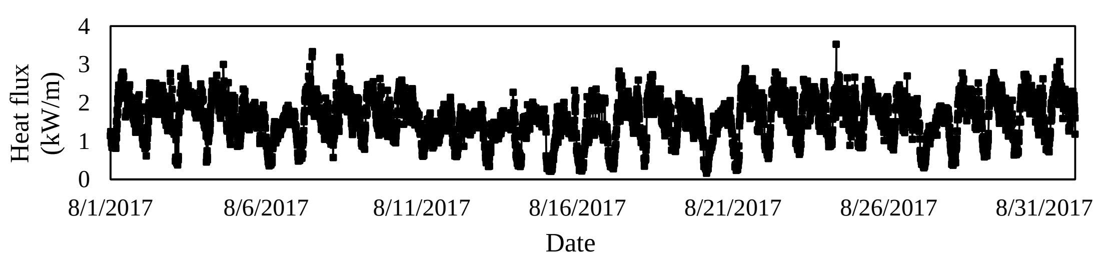

Fig. 2: Estimated vehicle heat flux between 19.89kp and 21.58kp.

2.2. Inlet and Outlet

This model is made from only one part of tunnel, so there is axial air movement due to traffic effect. It can be known from data that Temperature in outlet spot is higher than inlet, suppose air is incompressible and air mass flow rate is same on both sides, then we have

$$Q_{outlet} = c_{air}\rho_{air}v_{outlet}S(T_{outlet} - T_{inlet}) \qquad V_{outlet} = Sv_{inlet} + V_{vinet} - V_{voutlet} \tag{2}$$

ρ_{air} and c_{air} represent density and heat capacity of air. Inlet and outlet air flow velocity, temperature in traffic direction are denoted as v_{inlet} and v_{outlet}, T_{inlet} and T_{outlet}. Air flow amount due to inlet and outlet of ventilation system are defined as V_{vinet}, $V_{voutlet}$. Tunnel cross section area S is 63.3 m^2.

2.3. Ventilation

The ventilation of road tunnel is to control the pollutant concentration and visibility in tunnel effectively, and exchanging heat with ambient air. The calculation length 1690m is subjected to transverse ventilation system, heat extracted by ventilation can be calculated by

$$Q_{ventilation} = c_{air}\rho_{air}\Delta V_{ventilation}(T_{outlet} - T_a) \tag{3}$$

$$c_{air}\rho_{air}(v_{inlet}S + V_{vinet})T_a = c_{air}\rho_{air}V_{vinlet}T_{vinlet} + c_{air}\rho_{air}v_{vinlet}ST_{inlet} \tag{4}$$

T_a is average air temperature inside tunnel, T_{vinlet} and $T_{voutlet}$ are inlet and outlet air temperature of ventilation system.

2.4. Asphalt Road Surface

Road surface absorbs a limited part of heat from vehicle, Prusa et al. (2002) [11] showed the quasi-steady energy balance in a certain range near the vehicle due to heat generated by itself, and evaluated the thermal fluxes generated by vehicles such as the surface thermal flux under the effect of frictional loss, radiant flux at the bottom, convective heat transfer that occurs between vehicle and the road surface.

Heat conductivity k has been calculated by data from wind-tunnel test as 0.89 W/m·℃, density is also determined after measuring the asphalt test specimen. In this study, complex heat exchange between road pavement and air inside tunnel will not be conducted. Instead, field measurement data has been used. Heat absorbed is calculated using

$$Q_{road} = k\frac{\partial \mathrm{T}_{as}}{\partial \mathrm{d}}\mathrm{W}\Delta t + 0.75\mathrm{DW}c_{as}\rho_{as}\Delta T_{as} \tag{5}$$

T_{as} and d are asphalt temperature and depth. W is road width. D is total depth of asphalt pavement. c_{as} and ρ_{as} are heat capacity and density respectively.

2.5. Wall Absorption

Heat absorbed by wall is mainly by convective heat transfer between air and wall. The convective coefficient h_c is estimated by using Colburn correlation as below

$$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{1/3} \qquad h_c = \frac{\lambda}{\mathrm{d}}\mathrm{Nu} \qquad Q_{wall} = h_c C(T_a - T_w)\Delta t \tag{6}$$

Nu is Nusselt Number, Re is Reynolds Number of air, Pr is Prandtl Number of air. h_c represents convective heat transfer coefficient. C is concrete wall perimeter. T_w is concrete wall temperature.

Table 1: Physical properties.

Air density ρ_{air}	1.127 kg/m^3	Radius of tunnel R	5.55 m
Specific heat of air c_{air}	1.005 kJ/kg·℃	Calculation length of tunnel L	1690 m
Asphalt density ρ_{as}	2360 kg/m^3	Cross section area S	63.3 m^2
Asphalt heat conductivity k	0.89 W/m·℃	Concrete wall perimeter C	23.25 m
Asphalt thickness d	0.08 m	Road width W	7.5 m
Asphalt heat capacity c_{as}	0.92 kJ/kg·℃	Heat conductivity of air	0.0271 W/m ·℃
Prandtl Number of air Pr	0.7		
Inlet and outlet air flow velocity	v_{inlet} v_{outlet}	Ventilation outlet air volume	$V_{voutlet}$
Average air temperature	T_a	Ventilation inlet air volume	V_{vinlet}
Inlet and outlet air temperature	T_{inlet} T_{outlet}	Ventilation inlet and outlet air temperature	T_{vinlet} $T_{voutlet}$
Convective heat transfer coefficient	h_c	Wall temperature	T_a

3. Validation and Suggestion

Based on the results above, the predicted inside air temperature at 21.58kp location is compared with real measurement data, it turns out to be the predicted air temperature variation is too large, although total energy is almost balanced in one day. This model needs to be made much more detailed in order to predict air temperature more accurately. In Fig. 3, it shows that each heat load changes during time in one day, ventilation extracted heat is more than other 3 kinds, which means most of traffic induced heat dissipates with air flow forced by ventilation system in transverse direction. To reduce temperature, compared with applying good thermal conductivity materials on wall or water-retaining asphalt on road, continuous air cooling methods are better to be adopted. For example, water mist spray inside tunnel is an economic and effective way to consider.

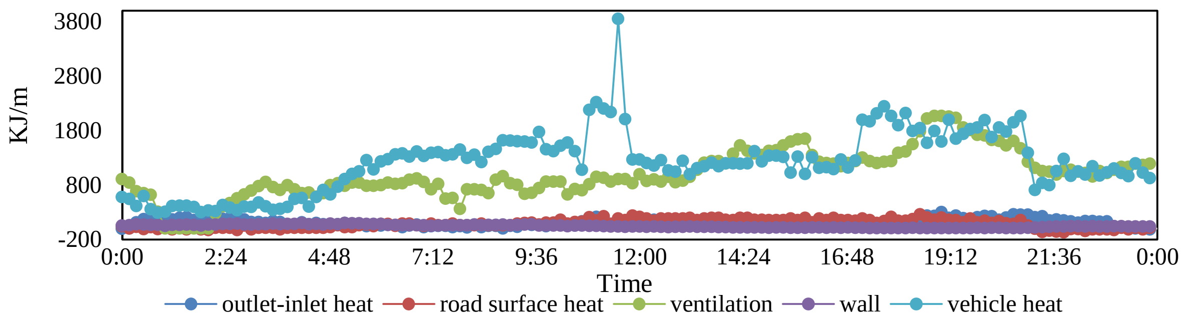

Fig. 3: Total heat gain and loss in 7th, Aug.

4. Conclusion

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 cause temperature rising. Most vehicle heat energy is extracted out by air flow inside tunnel. Cooling countermeasures must be concentrate on continuous air cooling methods as air flow carries most heat energy heated by running vehicle.

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