ASSESSING THE POTENTIALS OF ENERGY-SAVING STRATEGIES FOR AN UNDERGROUND MASS RAPID TRANSIT SYSTEM WITH PLATFORM DOORS

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Abstract

This study employs a subway environmental simulation program to analyze the effect of ventilation systems on energy use and assess the potentials of energy-saving techniques on the ventilation and air-conditioning (AC) systems under tropical climate for an underground mass rapid transit system with platform doors in Taipei (Taiwan). In the case of the outdoor air temperature of 32.2 °CDB and 26 °CWB and 120-second headway, even though the airflow rate of the under platform exhaust (UPE) increases to 50 m³/s, additional cooling capacity of 50 US refrigeration tons (USRT) from each station should be provided to keep the average air temperature of tunnel (connected both sides of the station) lower than or equal to the required tunnel air temperature (37 °C). Under the considerations of avoiding over-design and keeping the normal operation of train AC systems, increasing the temperature of tunnel air from 37 °C to 41 °C can save an average operating power of 44.7 kW per Celsius degree. Further increasing the tunnel air temperature (more than 41 °C) has no significant benefit on energy-saving. Moreover, in the case of 180-second headway at peak hours and 360-second headway at off-peak hours, the annual electricity saving for the UPE fans with variable air volume control exhibits 70%, 78%, and 83% of that for the UPE fans with constant air volume control in the cases of the combinations of UPE 30 m³/s/track and AC 100 USRT, UPE 40 m³/s/track and AC 80 USRT, and UPE 50 m³/s/track and AC 50 USRT, respectively.

1. Introduction

Air-conditioning (AC) is necessary to achieve acceptable conditions for an underground mass rapid transit (MRT) located in hot/tropical climate, such as Taipei City. However, the cost on electricity is huge, about 20 millions US dollars annually. Among the cost, about 40% of the electricity is attributed to AC [1]. Therefore, understanding the factors affecting electricity consumption due to AC and the potentials of various energy-saving strategies is very important to the operation and management of the MRT system. The AC system of an underground MRT is significantly more complicated than that of a commercial building. Specifically, the AC system of an underground MRT must incorporate design features of tunnel ventilation, and smoke exhaust. Installing platform doors at MRT systems benefits several advantages; keeping the heat and dust produced on the tunnel track from ingression to the platform area, and reducing the piston effect on the thermal condition and airflow draft in the platform area. However, the temperature in the tunnel area should be controlled to a certain value in order to keep the AC unit of the train functioning well. In the cities of northern hemisphere, the required temperature in the tunnel area can be achieved by introducing outdoor air due to the piston effect of a train moving in the tunnel [2], while in tropical areas, the required temperature in the tunnel area should be achieved by AC systems. The design capacity of tunnel exhaust air systems is, therefore, very crucial under the consideration of temperature control.

Fig. 1 schematically shows ventilation systems at the platform level of the MRT with/without platform doors. The heating, ventilation, and air-conditioning (HVAC) systems at MRT with platform doors is an “open cycle”, where the fans of under platform exhaust (UPE) and the piston effect of the train remove most of the heat produced in the tunnel. However, in some situations, additional AC is required to achieve the design temperature in the tunnel areas. Fan arrangements of an air-side system in the case of MRT with platform doors are shown in Fig. 1. The make-up air fan (MAF) brings in the outdoor air to mix with the return air from the return air fan (RAF) and finally supplies to the AC zone by the main supply air fan (MSF). When the enthalpy of the outdoor air is lower than that of the design condition of indoor, the MAF brings in the outdoor air. In such a case, the AC system only cools the public area of the station, but the heat produced in the tunnel is removed by both the piston effect...
created by the train and most remarkably by the suction effects of the UPE and the release well.

On the other hand, the HVAC systems at MRT without platform doors is a “closed cycle”, where the heat load in the tunnel is removed by the AC systems at the station and the piston effect of the train in summer and winter, respectively. There are only several MRT systems with platform doors in the world (e.g., Singapore and Hong Kong). Therefore, the available information on environment control system with platform doors is very limited, especially with respect to the energy aspect. Using the energy simulation program TRACE 600, Chow and Yu [3] studied the relationship of introducing ventilation air and energy consumption for mechanical ventilation and air-conditioning (MVAC) systems in train compartments in Hong Kong. They concluded that the electrical energy required to operate the MVAC system for each train compartment can be 4.4 times more than that without any ventilation. For the MRT system of Beijing, Zhu [4] found that the number of passengers and the outdoor air temperature affected the tunnel air temperature and MRT systems with platform doors could reduce the cost of HVAC. Tabarra et al. [5] pointed out that more sustainable approaches (including geothermal cooling, river, sea or groundwater cooling, or evaporative cooling) than traditional refrigeration cycles may be suitable. Hu and Lee [6] studied how platform screen doors (PSD) affect the energy consumption of the environmental control system of a MRT system in Taipei. The peak load for the case with PSD is only around half of that for the case without PSD. Consequently, installing PSD has the significant advantage of reducing peak cooling load. However, electricity consumption by ventilation equipment increases notably when PSD are used, particularly the electricity consumption by the UPE fans, and thus, ultimately, little difference exists in the overall energy consumption with and without UPE.

To the best knowledge of the authors, there has been no journal paper focusing on variable air volume (VAV) systems and energy conservation for the ventilation system of MRT stations with platform doors. In Taipei MRT systems, the constant air volume (CAV) system is used in the UPE fan which airflow rate is designed on the basis of peak load and peak point of the outdoor air in summer; hence, more energy is mostly consumed at partial load operation. This paper quantitatively analyzes energy consumption on VAV systems applied to the tunnel ventilation system of Taipei MRT station. This investigation aims to study the most crucial factors affecting energy consumption and to assess the potential of energy-saving strategies for the ventilation of MRT systems with platform doors.

2. SIMULATION PROGRAM

Parsons Brinkerhoff Company designed the SES program with the support of the Volpe National Transportation System Center of the United States Department of Transportation. This program has been applied to transit systems in more than forty cities [7], and verified by operational data from MRT systems in Montreal, Pittsburgh, San Francisco, Toronto, Washington and the Memorial Tunnel. Tropical climate applications of the program include Hong Kong and Singapore. The treatment of the tunnel heat loads is shown below.

![Fig.1: Ventilation system at platform level of MRT with/without platform doors](image-url)
2.1 Internal Heat Generation

(1) Train carriage heat load from passengers:
\[ q_{PS} = N_P \rho_{av} q_{SEN} \]  
(1)
\[ q_{PL} = N_P \rho_{av} q_{LAT} \]  
(2)
where \( q_{PS} \) is the total sensible heat loads from passengers (W), \( q_{PL} \) the total latent heat loads from passengers (W), \( N_P \) the passenger number per hour, \( \rho_{av} \) the average staying time of passengers (hr), \( q_{SEN} \) the sensible heat loads of one passenger (W), and \( q_{LAT} \) the latent heat loads of one passenger (W).

(2) Heat generated by the acceleration and braking mechanism [8]:

- The aerodynamic drag resistance:
\[ q_D = \frac{F_d d}{3600} \]  
(3)
\[ F_d = 1.41 \times 10^{-5} \alpha \delta C_D U^2 \]  
(4)
where \( q_D \) is the subway heat gain due to aerodynamic drag (W), \( F_d \) the aerodynamic drag force (N), \( d \) the stopping distance from maximum speed (m), \( n \) the number of trains per hour, \( a \) the frontal area of train (m²), \( \alpha \) the weight density of air (Nm⁻³), \( C_D \) the aerodynamic drag coefficient, and \( U \) the average train velocity (m⋅min⁻¹).

- The mechanical resistance can be computed from the empirical equation developed by Davis [8]:
\[ q_M = \frac{F_M d W N_C n}{3600} \]  
(5)
\[ F_M = 5.8 + 516/W + 7.4 \times 10^{-3} U \]  
(6)
where \( q_M \) is the subway heat gain due to mechanical resistance (W), \( F_M \) the mechanical resistance force of single car (N), \( W \) the weight of single car including passengers (tons), and \( N_C \) the number of cars per train.

- The resistor losses:
\[ q_r = KE + q_m \]  
(7)
\[ q_m \approx KE \left(1 - \frac{\epsilon_n}{\epsilon_m}\right) \]  
(8)
where \( q_r \) is the starting resistor losses for first step of cam-controlled series-parallel connection (W), \( q_m \) the subway heat gain due to traction motor losses (W), \( KE \) the kinetic energy (W), \( W_e \) the equivalent weight of single car including passengers and rotational inertia (tons), and \( \epsilon_m \) the traction motor efficiency.

(3) Heat generated by others:

- Heat losses of third rail:
\[ q_{3R} + q_{SR} = \begin{cases} \frac{2.22}{nt} \left(KE + q_D + q_M + q_m + q_{SR}\right) R \end{cases} \]  
(10)
\[ q_{SR} = 2q_r \]  
(11)
where \( q_{3R} \) is the third rail losses during acceleration (W), \( q_{SR} \) the starting resistor losses (W), \( R \) the combined contact and running rail resistance (milliohms), \( t \) the acceleration time (sec), and \( V_0 \) the third rail voltage (volts).

- Tunnel lighting:
\[ q_{TL} = W_L L \]  
(12)
where \( q_{TL} \) is the tunnel lighting heat rate (W), \( W_L \) the tunnel lighting (Wm⁻¹), and \( L \) the tunnel length (m).

- Accessories equipment of car:
\[ q_{AX} = 0.278 K_w f N_C n t \]  
(13)
where \( q_{AX} \) is the subway heat gain due to train accessories (W), \( K_w \) the input horsepower to car accessory motor (kW), \( f \) the percent of time motors in operation, \( t \) the time for single train to traverse station module (sec).

- Air-conditioning of car:
\[ q_{AC} = 1.32 T N_C n t \]  
(14)
where \( q_{AC} \) is the subway heat gain due to train AC (W), and \( T \) the AC per car (tons).

2.2 Transmission Heat Load

\[ q_{cond} = -\left(\Delta T\right)/R_{total} \]  
(15)
where \( \Delta T \) is the temperature difference between soil surrounding temperature and average subway
temperature (K), and $R_{total}$ the total thermal resistance (K/W).

### 2.3 Ventilation

\[ q_{\text{VENT}} = 1200Q \Delta T \]  

(16)

where $q_{\text{VENT}}$ is the rate of sensible heat removal or addition by ventilation (W), $\Delta T$ the temperature difference between average subway temperature and outdoor air temperature (K), and $Q$ the average ventilation rate (m$^3$s$^{-1}$).

### 3. OPERATING PARAMETERS

The present study simulates a tunnel ventilation system, as shown in Fig. 2, including six stations (No. 1 to No. 6 orderly) and seven tunnel sections connected to the stations. At this system, an MRT green line goes through these six stations in which another MRT line is cross at No. 3 station (named an intersection station). No. 3 and 4 stations and their adjacent tunnels are targets of this paper, while other stations and tunnels are boundary conditions employed in the SES simulation. The train (consisted of six cars) is assumed to have a longer 40-second stay at the intersection station for passenger transferring but a normal 25-second stay per station at others. As shown in Fig. 3, No. 4 station is a typical underground building connected by a concourse level, a platform level, and up and down tracks (including tunnel sections and a station section). The exhaust and release wells, connecting with fan rooms and the outdoor air, are located at either side of the station. Moreover, the section area of the release well is typical 20 m$^2$. The outlets of UPE are slots each size of 0.25 m width by 1 m length on both sides of the platform. Each track has a total of 46 evenly distributed slots to capture the heat generated from the train. UPE ducts are installed under the platform level and connected with exhaust shafts at both ends. Two sets of UPE fans are installed with each exhaust shaft to simultaneously proceed with the exhausting of hot air on the same side of both ends.

The efficiency of an UPE ($E_{\text{upe}}$) is defined as: $E_{\text{upe}} = \text{(heat removed by UPE)/(heat released by the train)}$. Concerning the actual operational experience, this study assumes $E_{\text{upe}} = 65\%$. Train’s performance and operational conditions are listed in Table 1.

#### Table 1: Operating parameters of the train

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Train speed</strong></td>
<td>80 km·hr$^{-1}$</td>
</tr>
<tr>
<td><strong>Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Initial acceleration on straight and level tracks</td>
<td>1.0 ms$^{-2}$</td>
</tr>
<tr>
<td>Maximum variation at operations of acceleration or deceleration</td>
<td>0.8 ms$^{-2}$</td>
</tr>
<tr>
<td><strong>Braking rate</strong></td>
<td></td>
</tr>
<tr>
<td>Normal braking</td>
<td>1.0 ms$^{-2}$</td>
</tr>
<tr>
<td>Emergency braking</td>
<td>1.3 ms$^{-2}$</td>
</tr>
<tr>
<td><strong>Car size (six cars per train)</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>23.5 m/car</td>
</tr>
<tr>
<td>Width</td>
<td>3.18 m/car</td>
</tr>
<tr>
<td>Weight (empty situation)</td>
<td>113 tons/car</td>
</tr>
<tr>
<td>Full-loaded</td>
<td>275 persons/car</td>
</tr>
<tr>
<td><strong>Heat source</strong></td>
<td></td>
</tr>
<tr>
<td>Heat released by the auxiliary system</td>
<td>28.64 kW/car</td>
</tr>
<tr>
<td>Heat released by each passenger (sensible heat)</td>
<td>135 W per passenger</td>
</tr>
<tr>
<td>Heat released by each passenger (latent heat)</td>
<td>68 W per passenger</td>
</tr>
<tr>
<td>Heat released by acceleration, deceleration and breaking</td>
<td>From simulation results of SES</td>
</tr>
</tbody>
</table>
Fig. 2: Node graph for the SES simulation
Fig. 3: Tunnel ventilation system at a typical station including release shafts X and Y, a platform level, under platform exhaust, and up and down tracks

4. RESULTS AND DISCUSSION

An environment control system of MRT systems consists of the tunnel ventilation system and the station AC system. MRT with platform doors results in the reduction of cooling load at the platform levels; however, much more airflow of tunnel ventilation system is required to offset the temperature rise in tunnels and it causes more power consumption. The required power of a fan is a function of its airflow rate, static pressure, and efficiency, which is proportional to cubic airflow rate of the fan at the variation of its speed (i.e., fan laws). The efficiency of the AC chiller and the UPE fan is assumed to be 4 (coefficient of performance; COP) and 80%, respectively. The monitored locations of tunnel air temperature are set at tracks between No. 2 and No. 5 stations. The combinations of UPE 30 m$^3$/s/track and AC 100 USRT, UPE 40 m$^3$/s/track and AC 80 USRT, and UPE 50 m$^3$/s/track and AC 50 USRT are applied to the six stations, in which the cooling load (USRT) of AC equipment means the total heat (the sum of sensible heat and latent heat). Several strategies on energy saving are proposed and assessed here.

4.1 Planning a Suitable Design Value of Tunnel Air Temperature

The heat dissipation from trains results in the increase of tunnel air temperature and affects the operation of train AC condensers. The temperature of tunnel airflow will be affected significantly by the airflow rate of UPE, the outdoor air temperature and the passengers inside the train. Results show that the peak temperature of the tunnel air happens at the station section when the train stops at the station. The tunnel air temperature as stipulated in the design guideline is set to 37°C [9]; however, the allowable tunnel air temperature is determined by manufacturers of the train AC equipment and could be considered to be raised subject to no great impact on the normal operation of the train AC system. Under more safe and conservative consideration for the train AC system, a lower design value of tunnel air temperature should be required; therefore, it means that more energy should be consumed. This study would provide consultants some useful information on setting up the design guideline of tunnel air temperature to prevent over design at MRT stations (e.g., purchasing the train AC equipment subject to allowable higher temperature operation of the outdoor air and raising the design value of tunnel air temperature).

The conditions examined here are as follows: train headway of 120 seconds, outdoor air peak temperature of 32.2°CDB and 26°CWB, and peak hour at 17:00. Fig. 4 represents the relationship between the airflow rates (0 to 60 m$^3$/s/track) of UPE and the average temperature of tunnel air (54.3 to 38.5°C). It can be found that the temperature of tunnel air is more than 37°C even though the UPE reaches to the simulated maximum airflow rate (60 m$^3$/s).

Fig. 5 shows the variation between average air temperature of tunnels and power consumption of tunnel ventilation systems. In order to maintain the average tunnel air temperature lower than or equal to 37°C, the combination of the UPE of 50 m$^3$/s/track and additional AC of 50 USRT is required, while its corresponding power consumption for tunnel cooling is 215.8 kW. Increasing the average air temperature of tunnels from 37°C to 41°C results in savings in operating
power of average 44.7 kW/°C (i.e., approximately 294,000 kWh/°C/year; 365 days per year, and 18 hours per day). Further increase in average tunnel air temperature (more than 41°C) has no significant benefit on energy-saving. From the point of energy-saving on HVAC systems, it is therefore recommended that any one temperature, corresponding to its airflow rate of UPE and power consumption, among 37 to 41°C could be considered to be as a design value of the tunnel air temperature; however, it should firstly satisfy that the train AC system shall function well under the selected tunnel air temperature.

For keeping the average tunnel air temperature lower than or equal to 37°C, an airflow rate of UPE 50 m³/s/track, 40 m³/s/track, and 30 m³/s/track is provided with an additional AC cooling capacity of 50 USRT, 80 USRT, and 100 USRT at every station, respectively. Fig. 6 presents the hourly power consumption in the case of the combination of UPE 50 m³/s/track with variable frequency control (VFC) and AC 50 USRT. The power consumption from June through September are significantly higher (approximately 215.8 kW) than those in other months at peak hours, while the UPE fans are operated at partial load and their airflow rates are under VFC except from June through September.

4.2 Adopting Variable Frequency Control for UPE Fans

This study has also analyzed the monthly hourly power consumption of tunnel ventilation and AC systems, based on the annual weather data of Taipei city in 2005. The hourly average outdoor air temperature per month [10] is used to simulate the required monthly hourly airflow rate of UPE fans in the SES program, and then the required power can be calculated from a power formula and fan laws. In designing the tunnel ventilation system, the 120-second headway is usually required by clients for conservative and safe consideration, although the trains are actually operated at 180-second headway. In order to meet with the true operation of MRT system in Taipei city, the power consumption of the UPE fans and the AC chillers here is subject to the following conditions: train headway of 180 seconds at peak hours (7:00–9:00 a.m. and 4:00–7:00 p.m.), the headway of 360 seconds at off-peak hours, and average tunnel air temperature lower than or equal to 37°C.
operating airflow rate to the rated airflow rate for UPE 30 m$^3$/s/track is larger than the one for UPE 40 m$^3$/s/track or 50 m$^3$/s/track. However, at or close to full load operation of the UPE fans in four months (from June through September), the ratio of the operating airflow rate to the rated airflow rate among UPE 30, 40, and 50 m$^3$/s/track is not much different, but the larger airflow rate fan consumes more electricity than the smaller one. As revealed in Fig. 7, in July, the peak electricity consumption (47,142 kWh) is happened at the combination of UPE 50 m$^3$/s/track and AC 50 USRT, the combination of UPE 40 m$^3$/s/track and AC 80 USRT consumes the electricity of 45,626 kWh, and the least electricity consumption (42,368 kWh) is at the combination of UPE 30 m$^3$/s/track and AC 100 USRT.

Fig. 7: Monthly consumed electricity at different combinations of the UPE fans with VFC and the AC chillers (180-second headway at peak hours and 360-second headway at off-peak hours)

Fig. 8 shows the annual electricity consumption at different airflow rates of the UPE fans with or without VFC. The annual electricity consumption of the AC chillers and the UPE fans with VFC in the order from higher to lower is 225,669 kWh (UPE 30 m$^3$/s/track + AC 100 USRT), 206,350 kWh (UPE 40 m$^3$/s/track + AC 80 USRT), and 193,276 kWh (UPE 50 m$^3$/s/track + AC 50 USRT). The combination of the higher UPE and lower AC, therefore, benefits more energy-saving throughout the year. The annual consumed electricity for the UPE fans with VFC exhibits 30%, 22%, and 17% of that for the UPE fans without VFC in the cases of UPE 30 m$^3$/s/track (with AC100 USRT), UPE 40 m$^3$/s/track (with AC 80 USRT), and UPE 50 m$^3$/s/track (with AC 50 USRT), respectively. In the case of no UPE fans actuated (i.e., only the piston effect of trains), even though the temperature of outdoor air lowers to 6°C, the tunnel air temperature will be more than 37°C. Therefore, the UPE 10 m$^3$/s/track is required at least to keep the tunnel air temperature lower than 37°C. It is found that the tunnel air temperature is lower than 37°C at UPE 50 m$^3$/s/track when the outdoor air temperature does not exceed 26°C; accordingly, the fan of UPE 50 m$^3$/s/track could be respectively unloaded to UPE 40 m$^3$/s/track or UPE 30 m$^3$/s/track by VFC when the outdoor air temperature is lower than 24°C or 22°C.

The number of trains moving in tunnels is determined by their headway. Longer headway results in fewer trains moving in tunnels and less heat generated from trains. The heat dissipated into tracks increases tunnel air temperature. As shown in Fig. 10, the headway has great impact on the tunnel air temperature at different airflow rates of UPE. In the case of 120-second headway, the temperature of tunnel air is higher than 37°C at any airflow rates of UPE, even though the airflow rate...
of UPE increases to 50 m$^3$/s/track. In such a case, additional cooling capacity from the AC system should be provided to keep the tunnel air temperature lower than or equal to 37°C. For headway larger than 300 seconds, the piston effect of train moving in the tunnel reduces the tunnel air temperature lower than or equal to 37°C.

- In order to keep the tunnel air temperature not more than 37°C, additional AC cooling capacities of 50 USRT, 80 USRT and 100 USRT from each station are incorporated with the UPE airflow rates of 50 m$^3$/s/track, 40 m$^3$/s/track and 30 m$^3$/s/track, respectively.
- The annual electricity saving for the UPE fans with VAV control exhibits 70%, 78%, and 83% of that for the UPE fans with CAV control in the cases of the combinations of UPE 30 m$^3$/s/track and AC 100 USRT, UPE 40 m$^3$/s/track and AC 80 USRT, and UPE 50 m$^3$/s/track and AC 50 USRT, respectively. The combination of UPE 50 m$^3$/s/track and AC 50 USRT saves the most energy.
- The combination of UPE 50 m$^3$/s/track and AC 50 USRT saves the most energy.
- In the case of no UPE fans actuated (i.e., only the piston effect of trains), even though the temperature of outdoor air lowers to 6°C, the tunnel air temperature will be higher than 37°C. Therefore, the UPE 10 m$^3$/s/track is required at least to keep the tunnel air temperature lower than or equal to 37°C (the current upper limit temperature of tunnel air).
- For headway of 120 seconds, the temperature of tunnel air is higher than 37°C at any airflow rates of UPE, even though the airflow rate of UPE increases to 50 m$^3$/s/track. For headway larger than 300 seconds, the piston effect of train moving in the tunnel reduces the tunnel air temperature lower than or equal to 37°C.

**ACKNOWLEDGEMENT**

The authors would like to thank the National Science Council (ROC) for financially supporting this research project (Project No. NSC 94-2623-7-027-004-EF), and the chief editor and reviewers for their valuable comments and helpful suggestions.

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