
Daniel Hii

Anthropogenic heat contribution to air temperature increase at pedestrian height in Singapore's high density Central Business District (CBD)

Daniel Hii Jun Chung, Wong Nyuk Hien, Steve Kardinal Jusuf
Department of Building, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566, dhjc@nus.edu.sg

Abstract

The high rise, high density urban environment of tropical hot and humid Singapore receives sunlight throughout the year, which is the main source of heat. The population density is also among the highest in the world with among the biggest energy consumption per capita (Lindberg et al., 2013) and about double the motor vehicle ownership than the nearest city with comparable population density (Hong Kong). This means the anthropogenic heat sources contribution is significant. The paper looks into the contribution of anthropogenic heat sources in affecting the air temperature rise at the densest area in Singapore in the CBD via site measurements. Results show that the contribution from anthropogenic heat sources do affect the air temperature rise in the urban canyon. Later, the research models the contribution of the heat from vehicles in the CFD (Computational Fluid Dynamics) environment. The aim is to understand how urban morphology can affect the air temperature profile inside the urban canyon with the contribution from the vehicles as the main anthropogenic heat source at pedestrian level.

Keywords: tropical, high rise, high density, anthropogenic heat, pedestrian height, site measurement, CFD

1. Introduction

Half of the world's population today live in cities, causing intensification of urban developments (UN, 2008) created from man-made materials that generate and retain heat. This generates an urban climate which is hotter than its surroundings, generally known as the Urban Heat Island (UHI) effect. Human beings are anthropogenic heat sources which contribute to this increased thermal pollution in cities via human metabolism, buildings and vehicles (Sailor and Lu, 2004) apart from the sun and sky which form the natural sources under the Urban Energy Balance inputs (Oke, 1987). In dense cities like Singapore, motor vehicles ownership is double the amount of Hong Kong with almost identical population density as well as built density based on the Height-to-Width (H/W) Ratio (LTA, 2014; Ng, 2009). It measures how close buildings are built to each other. It normally increases with the temperature difference between the urban and rural areas (Roth, 2013) and when population in cities increase (Oke, 1973) as an indicator of density.

Computational Fluid Dynamics (CFD) is used to study various aspects of the urban environments for the last 50 years (Blocken, 2014). It has the advantage over the energy balance model as it does not decouple temperature and wind flow (Toparlar, et al., 2014). Urban canyon studies are done more commonly to understand flow behavior and the surface convective heat transfer aspects. In terms of contribution from the climate sources, (Bottillo et al., 2014; Nazarian and Kleissl, 2014; Toparlar et al., 2014) have studied it but at lower H/W Ratios of up to 2. Contributions from buildings alone are studied by Huang et al., 2005; Rajagopalan and Wong, 2009; Hashimoto et al., 2014 while Chen et al., 2009 studied it together with vehicles contribution. Chen et al, 2009 showed that the impact from the traffic is the highest at the pedestrian level regardless of whether it is a high rise or low rise district. For all the cases that consider heat reject from buildings even from the vertical walls, the impact is still not as significant as vehicles.

The research is exploring into the contribution of anthropogenic heat at pedestrian level to air temperature increase in the densest part of Singapore, which is located in the CBD at microscale to local. This is classified as Local Climate Zone 1 which is compact high rise (Stewart and Oke, 2012). An anthropogenic heat inventory method study was done in Singapore (Quah and Roth, 2012) which shows that the commercial area has bigger contribution than high rise apartments and landed housing with more heat on weekdays during office hours. The buildings contribute the most, followed by vehicles and human metabolism. However, at pedestrian level, substantial contribution from the vehicles is expected since most heat waste from commercial buildings are released at the podiums or rooftops. Past measurements suggest 1°C contribution (Jusuf and Wong, 2009).

2. Methodology & Results

The investigation into the contribution of anthropogenic heat at pedestrian level is done by first looking at the ambient temperature of the CBD site. Later, roadside measurements are done at the pedestrian level to be closer to the sources of heat, which are coming from the vehicles. Finally, the CFD simulation is used to simulate the vehicles as heat sources to see how they are impacted by urban form and density.

2.1 Weather Stations

Onset weather stations were mounted 3.5m above ground around the Tanjong Pagar and Raffles Place area at 10 locations as shown in Figure 1. Their locations were selected for various reasons from nearest to anthropogenic heat sources (multi-storey carpark entrance, taxi stand, bus stop, barbeque stalls, traffic light junction) to site features (overhead bridge, water fountain, high aspect ratio canyon) as well as baseline conditions inside a park and the edge of the street canyon.

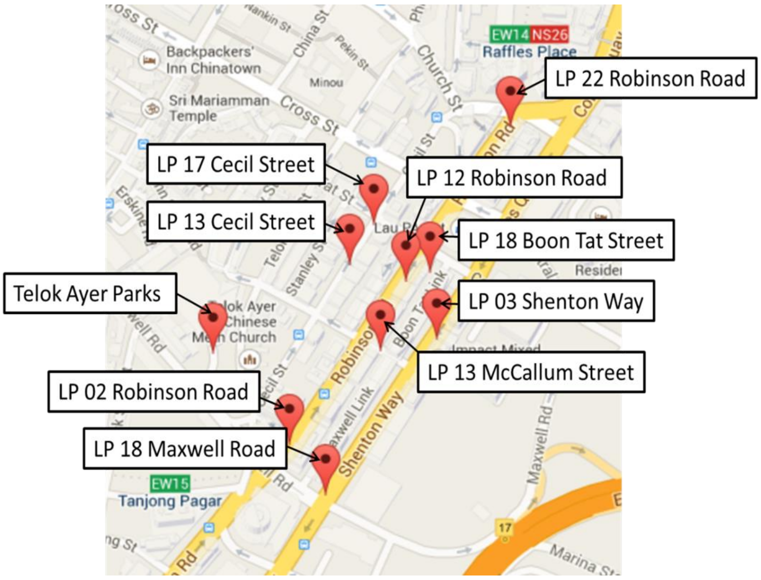

Fig. 1 Location of the weather stations in the CBD area.

The average weekday and weekend air temperature was taken from the ten locations in February 2014, when it was the driest month since 1869 (Today, 2014). Weekdays generally show higher air temperature than weekends apart from the traffic light junction location which is located in between the perpendicular and parallel urban canyons as shown in Figure 2. Although the difference may seem negligible at this height, it does appear more apparent when closer to the ground at pedestrian height for the roadside measurements later.

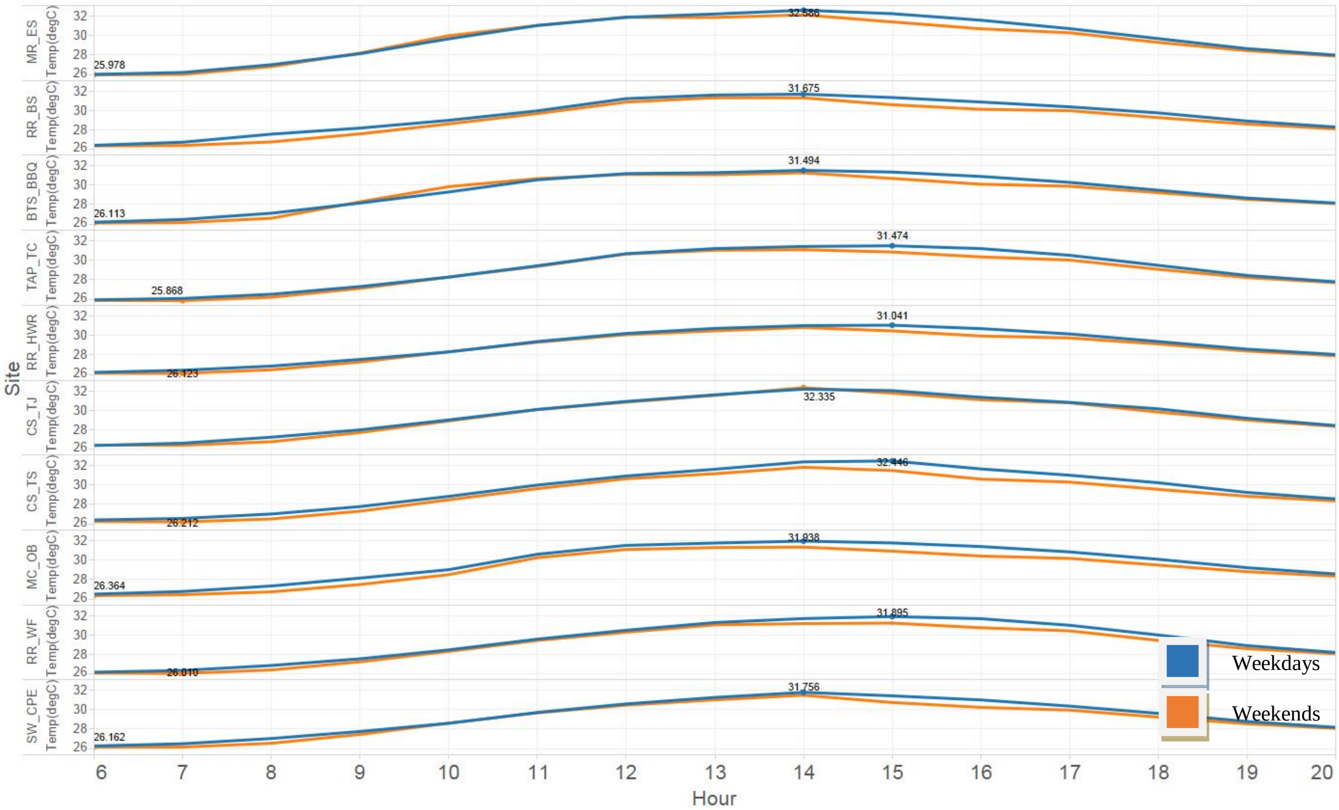

Fig. 2 Weekdays and weekends (February 2014) air temperature at 3.5m above ground (MR_ES=Maxwell Road_Edge of Site, RR_BS=Robinson Road_Bus Stop, BTS_BBQ=Boon Tat Street_Barbeque Stalls, TAP_TC=Telok Ayer Park_Trees Canopy, RR_HWR=Robinson Road_High Height-to-Width Ratio, CS_TJ=Cecil

Street_Traffic Junction,, CS_TS=Cecil Street_Taxi Stand, MC_OB=McCallum Street_Overhead Bridge, RR_WF=Robinson Road_Water Feature, SW_CPE=Shenton Way_Car Park Entrance).

2.2 Roadside Measurement

A roadside measurement at 1.5m height was done near a bus stop in a deep canyon at the same site during the afternoons of the same month. Air temperature measurements were taken from Onset, Aeroqual and Testo devices while the Fluke thermal imager is used to capture surface temperature as shown in Figure 3.

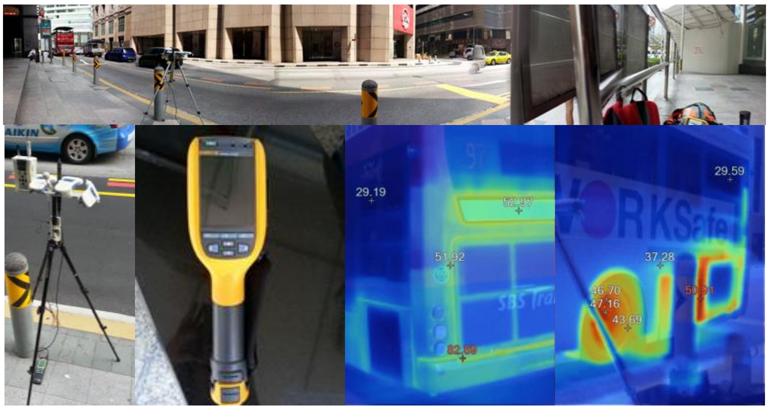

Fig. 3 CBD urban canyon roadside measurement (above), measurement equipment (below left) and infrared images of bus surfaces (below right).

The measurement records a maximum air temperature difference of 4.5°C during the peak hour between absence and presence of buses with higher temperatures recorded during weekdays as shown in Figure 4. The average air temperature is higher during weekdays with higher frequency of traffic volume than weekends. The human traffic around the pavement is high during weekdays too but the contribution to the air temperature rise should be negligible. The captured air temperature difference near the ground is higher than those recorded higher on the weather stations as it is closer to the heat sources.

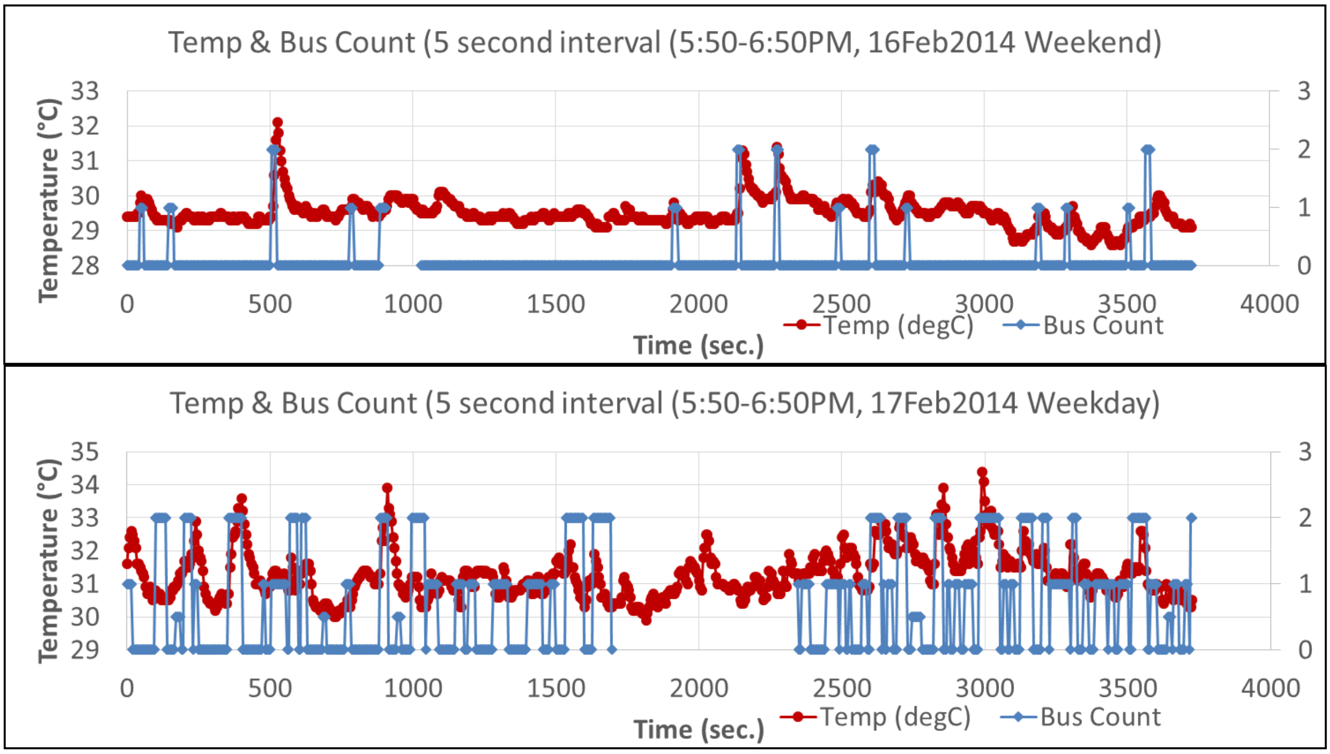

Fig. 4 Air temperature against bus count during weekday and weekend.

2.3 CFD Simulation

A 6am-6pm slab and points street canyon of H/W ratio of 2 and 4 with as well as without double decker buses were simulated in the transient CFD environment with perpendicular and parallel flow as shown in Figure 5. ANSYS Fluent 14 was used for the simulation with the realizable k-ε turbulence model for closure. The solar radiation was activated with S2S (Surface-to-Surface) radiation model, using Boussinesq approximation for buoyancy with gravity enabled. The wind speed of 2.3m/s at 15m above ground (averaged from the Changi Meteorological Station's 16 wind directions between 1999 and 2008) was used to generate the urban wind profile with power law coefficient of 0.32. The 4m typical façade height of the buildings consisted of window to wall ratio of 0.475, having 2.1m of aluminium cladding and 1.9m of glass (window). The initial air temperature of 25.75°C was used for the simulation at 6am, taken from a weather station at the site. The double decker buses at the center of the canyon are assumed to be idling heat sources generating heat from the back at the exhaust area.

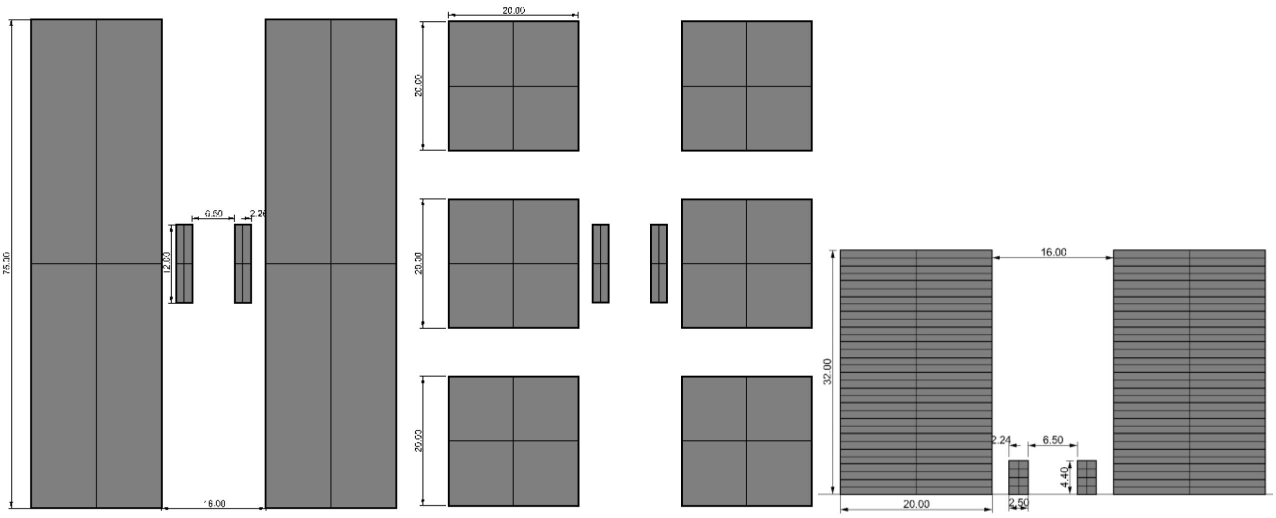

Fig. 5 Slab (left) and point (center) typologies in plan and elevation (right).

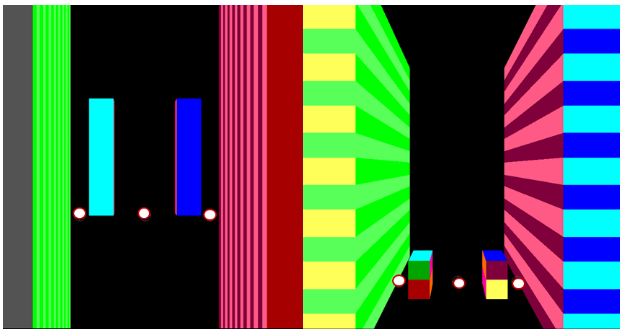

Fig.6 Point measurements taken from 3 locations at 1.5m above ground in the canyon.

Measurements at the pedestrian height at the pavements record air temperature increase of close to 3°C between cases with and without buses as shown in Figure 8. Cases with parallel flow regulate air temperature inside the canyon better than perpendicular flow. Therefore, it is clear that urban canyons that receives parallel flow enjoys better average wind speed and hence lower air temperature. The heat from the buses can be transferred out of the canyon better with parallel flow and do not retain in the canyon to higher elevations like the perpendicular flow as shown in Figure 7. Higher H/W ratio cases generate better channeling effect for parallel flows while retaining higher air temperature for perpendicular flow.

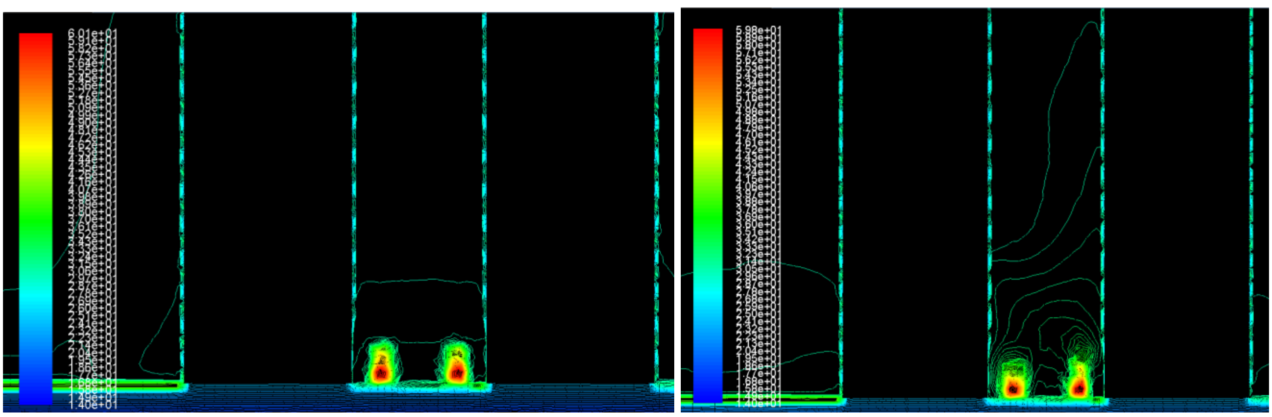

Fig.7 Urban Canyon elevation of parallel flow (left) and perpendicular flow (right)

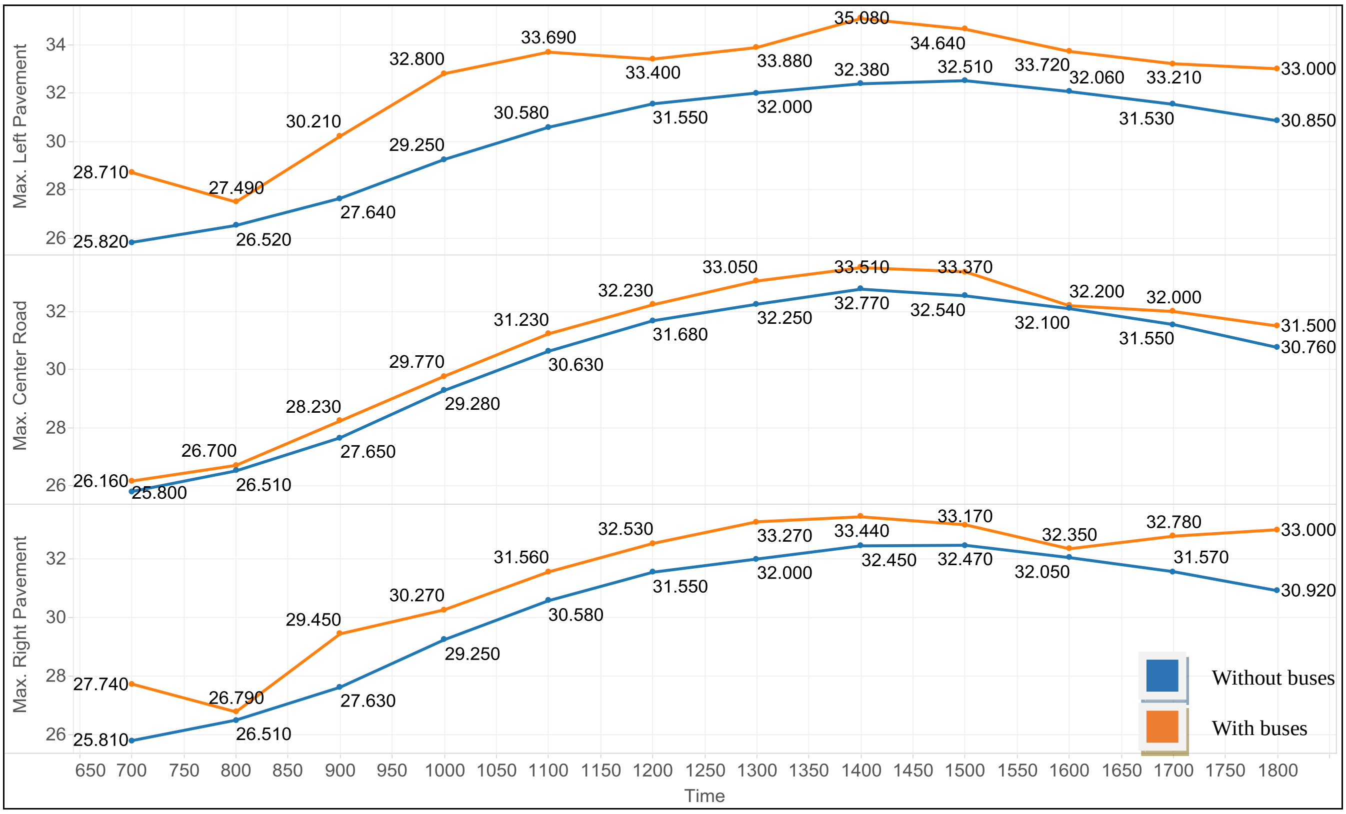

Fig. 8 Point measured air temperature with and without bus heat at 1.5m in the urban canyon for point and slab typologies for both parallel and perpendicular wind flow.

3. Conclusions and Future Works

In conclusion, the weather stations and the roadside measurements suggest that anthropogenic heat particularly from vehicles contribute to air temperature increase at pedestrian level in the CBD area. The CFD simulation results show that form and density does affect the flow and heat transfer in the canyon. Further investigation needs to be done to explore various forms at high densities to determine if there is/are any good geometric variable/s can help predict ventilation and heat dissipation performance at pedestrian level. What is clear at this stage is more openness or permeability/porosity at the pedestrian level will definitely help.

For future studies, parametric studies will be done for the worst case scenario on March 20th at 2pm when it is hottest and the road is filled with vehicles following the local statistics (LTA, 2014), mimicking the peak hour with the impact of various urban morphologies with wind flow from parallel, perpendicular and diagonal directions as shown in Figure 9. Future technology like adopting electric vehicles will help minimize the problem since they emit just 19.8% of total heat emitted by conventional vehicles.

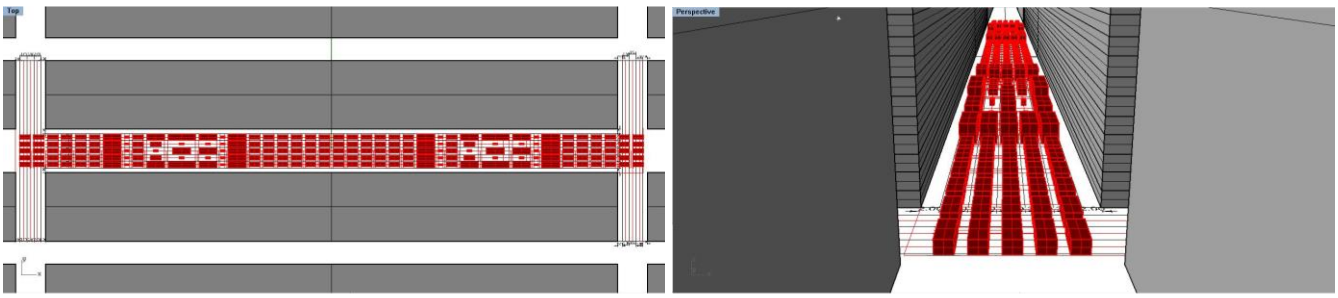

Fig. 9 Urban canyon filled with vehicles in plan (left) and elevation (right).

Acknowledgment

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