A case study of environmental characteristics on urban road-surface and air temperatures during heat-wave days in Seoul

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ABSTRACT
High road-surface temperature due to heat waves can lead to dangerous driving conditions such as tire blowouts and deformation induced by thermal stress on the roads. In this study, a Mobile Observation Vehicle dataset, with high spatial and temporal resolutions for the heat-wave episode that occurred on 16–17 August 2018, is used to understand environmental characteristics on urban road-surface and air temperatures in Seoul. This study demonstrates that the magnitude of urban road-surface temperature is dependent on the differences in incoming solar radiation due to screening of high-rise buildings in the Gangnam area, and is associated with the topographical features in the Gangbuk area. The road-surface temperature in the section of darker-colored asphalts was higher than that of lighter-colored asphalts, with a mean difference of 6.8°C, and both surface and air temperatures on the iron plate were highest, with means of 51.7°C and 35.1°C, respectively. In addition, during the water-sprinkling period, road-surface temperature was cooled by about 8.7°C (19%) compared with that in the period without water-sprinkling, but there was no significant change in air temperature. The current results could be practically used to improve road-surface temperature prediction models for civil engineers or road managers.

1. Introduction

Heat waves are one of the major meteorological disasters because they can affect many aspects of human life, such as through their impacts on health, socioeconomics, drought, and roads (Schwartz 2005; Barnett 2007; Schubert et al. 2014; Kim et al. 2017). Extreme road-surface temperatures can lead to dangerous driving conditions due to high air temperatures, snow, black ice, and fog. In winter, a road-surface temperature forecast is essential information for highway engineers, allowing cost-effective salting decisions regarding winter road maintenance (Feng and Feng 2012). On the other hand, in summer, high surface temperatures can cause tire blowouts and deformation induced by thermal stress on the rails or roads (Campbell 2008).

There have been lots of observational and model studies on the characteristics of air temperatures or road-surface temperatures as a standalone variable all over the world. Synnefa, Karlessi, and Gaitani (2010) suggested that cool coloured asphalt could reduce road-surface temperatures in hot urban areas, based on experimental testing. Feng and Feng (2012) conducted a comparative analysis between the prediction and observation of the road-surface temperatures from two road weather stations on a highway. Higashiyama et al. (2016) evaluated the surface temperature of several asphalt pavements with a temperature rise reduction function through field measurements in the summer season. Zhao, Zha, and Wu (2018) compared urban-related warming in terms of air temperature in two cities of southern China using the Weather Research and Forecasting regional climate model. However, most previous studies have been conducted on either road weather or heat waves/the urban heat island (UHI) effect. Although heat waves and road weather are inextricably linked, and have socioeconomic impacts, there have been very few studies that have combined these topics. In 2018, the highest temperature recorded in Seoul, the capital city of Korea, since the government started compiling the data in 1907, was 39.6°C (Korea Meteorological Administration), and at the time of writing 48 people had died of heat stroke and 4526 people had been taken to hospital for heat-related illnesses in Korea (Korea Centres for Disease Control and Prevention).

Numerous investigations on socioeconomic vulnerability in relation to heat waves have been carried out so far. In general, urban areas during the heat-wave period can accelerate the increase in air temperature more than in rural areas due to the UHI effect, and can also raise road-surface temperatures (Synnefa, Karlessi, and Gaitani 2010). Since pavements cover a high percentage of the urban area, the local road-surface temperatures can be
substantially influenced by the types of material (Synnefa, Karlessi, and Gaitani 2010; Guan 2011; Higashiyama et al. 2016). In addition, the magnitude or variability of road-surface temperature is dependent on several factors, such as the arrangement of buildings, incoming solar radiation, shading, topography and traffic (Shao et al. 1997; Bogren et al. 2000; Chapman and Thornes 2005; Ha, Lee, and Park 2016).

Despite progress made in road weather information systems (RWISs), the performance of road-surface temperature prediction models is still limited in areas with sparse observations (Chao and Zhang 2018). Seoul has the highest traffic volume in Korea, but only a small number of RWIS sites. Meteorological factors such as air temperature or wind are also important for predicting road-surface temperature (Solaimanian and Kennedy 1993; Offerle, Eliasson, and Grimmond 2007). Therefore, a well-designed observation framework based on mobile platforms with both road-surface and meteorological sensors is required to capture accurate road-weather information in vulnerable regions.

Different to previous studies largely based on road weather in winter (Shao et al. 1997; Postgård and Lindqvist 2001; Chapman and Thornes 2005), the purpose of the present study is to investigate the characteristics of road-surface and air temperatures at the urban microscale on heat-wave days. A Mobile Observation Vehicle (MOVE) dataset, with high spatial and temporal resolutions for the heat-wave episode that occurred on 16–17 August 2018, is used to understand the environmental characteristics on road-surface and air temperatures in Seoul.

2. Data and observational method

To compare characteristics of road-surface and air temperatures in two sectors with different local features, we selected urban roads in southern (Gangnam) and northern (Gangbuk) areas of Han River, which have high-rise buildings and some mountains, respectively. In general, the topographical variation is small in the Gangnam area, whereas the screening effect of buildings is small in the Gangbuk area. Here, we discuss the heat-wave episode that occurred on 16–17 August 2018, for both urban roads. The MOVE dataset used in this study was generated by equipment that included road weather sensors and an air temperature probe and radiation sensors. A detailed schematic diagram of MOVE and information on the instruments is presented in Figure 1(a). All data were collected at a 1-s rate, were displayed in real time, and transmitted to a server within 5 min using machine-to-machine technology. Quality-checked algorithms developed by Park et al. (2017) were used for data-processing based on the MOVE platform.

MOVE was driven on an urban road along the main sectors of Seoul city. Road-surface and air temperatures were obtained with a surface patrol infrared sensor (DSP101, Vaisala, Vantaa, Finland) and an air temperature probe (HMP155, Vaisala, Vantaa, Finland), respectively. Solar radiation was determined by a pyranometer (CMP11, Kipp and Zonen, Delft, Netherlands). The operating air temperature of the DSP101 sensor ranges from −40 to +71.1°C, and the response time (63%) of the HMP155 and CMP11 sensors are less than 20 s and 0.7 s, respectively, which meet the guideline levels of the World Meteorological Organization (WMO 2012). To minimize the impact of nearby vehicles, we kept enough distance, and the cruise control was set at 30–40 km h⁻¹, except in traffic jams. In addition, we designed optimal observation routes and times, as shown in Figure 1(b,c), for a relative comparison of characteristics of both urban roads under a similar synoptic pattern and solar elevation. The total distances of both observation routes were 14 km and 21 km, respectively.

3. Results

3.1. Screening effect on urban road-surface temperature

The UHI effect can also strengthen heat waves, which is determined by the city size and increase in building density (Atkinson 2003; Loughner et al. 2012). In this section, the screening impact of urban buildings on the road-surface temperature during the heat wave in Gangnam, one of the regions with the highest urban canopy layer in Korea, is examined, and the combined MOVE data were used to investigate how air temperature and solar radiation are related to road-surface temperature. First, the distribution of air temperature is compared with that of road-surface temperature (Figure 2(a,b)). It is interesting to note that the distributions of surface and air temperature were not consistent, despite the same observation time. Air temperature showed a maximum (37.8°C) at the Gyeongbu expressway section (red triangle marked in Figure 2(a)), whereas the road-surface temperature showed a tendency that the east–west section was higher than the south–north section, except for the Gyeongbu expressway section (Figure 2(b)).

Figure 2(c) shows the differences between air and road-surface temperature during MOVE’s route. The signature of the difference field exhibited a result similar to that of the spatial distribution of surface temperature. To confirm these relationships with spatial structure in the vicinity of urban roads, we also examined a 3D map from the Vworld web service. The open-platform-based Vworld map service is operated under the sponsorship of the
A 3D map view in the section where the difference in temperature is the smallest (−1.6°C; reversal of temperature) shows a concentration of high-rise buildings over 20 m (Figure 2(e)). In this regard, we considered that the road-surface temperatures in that section were affected by the screening due to surrounding buildings.

Additional noteworthy findings to support the above results are presented in Figure 2(d). We found the distribution of solar radiation to have comparatively similar patterns and good agreement with those of surface temperature and the difference in temperature, as shown in Figure 2(b,c). At 0600 UTC in Seoul, the solar altitude and azimuth are 50° 13′21.1″ and 242°53′21.8″, respectively (from Korea Astronomy and Space Science Institute), which means screening is more likely on roads opposite to urban buildings in the direction of solar radiation (Figure 2(e)). These results might be associated with the amount of incoming solar radiation. That is, it is suggested that the magnitude of urban road-surface temperature is mainly caused by screening impacts such as the differences between sun-exposed and shading sections due to high-rise buildings.

3.2. Variation in road-surface temperature due to topography

This section focuses on the northern (Gangbuk) area of Han River, as shown in Figure 3(a), which includes mountains and has some tunnels near Mount Nam. The Han River flows from the east to west of Seoul, and some mountains are mainly located in the north. On 17 August (the day after observation in Gangnam), road observation using the MOVE platform was also carried out along a 21-km stretch of urban road around the Yongsan-gu and Jung-gu regions of Seoul, together with specific site measurements by two automatic weather stations (Figure 1(c)). We discovered that the sensors mounted on MOVE are comparable to those of fixed sites. Figure 3(b) shows sharp changes in altitude within a range of 400 m on the surveyed road, despite
relatively short distances. We identified two altitudinal peaks on the road, near Mount Nam and Yongsan park, and a significant difference in altitude between the southern (between 0508 and 0530 UTC) and northern (other periods) sections.

In order to investigate the variations in air and road-surface temperature according to the topography, we calculated the anomalies of each temperature and average values and then presented them as vertical bars, as shown in Figure 3(b). The mean air and surface temperatures during the observation period were 32.1°C and 49.0°C, respectively. Interestingly, the results show that the road-surface temperature is associated with topographical features, except for some sections. To identify the section of any significant change of local topography, the observation period was divided into three sections (A, B, and C), as marked in Figure 3(a,b). In all three sections, the road-surface temperatures showed a tendency of negative anomalies, which may be attributable to the influence of surrounding soil (or grass) surfaces and a larger cooling rate at relatively higher altitude. However, it should be noted that the relationships are nonlinearly mixed and rather complex (Shao et al. 1997). On the southern road of the Gangbuk area, where the altitude is relatively low, we found a tendency with positive anomalies of about 5°C persisted for about 30 min (Figure 3(b)).

However, there were no significant characteristics of the relationship between air temperature above the road and topography from our examination. One thing to note is that the air temperatures appear to have a different phase around 0500 UTC. Therefore, we
found that air temperatures were more dependent on the diurnal variation than the topographic effect. Finally, for probing the basic characteristics pertaining to the thermal variations of urban tunnel environments, we further investigated the impacts on road-surface and air temperatures in the section of Namsan3 tunnel (Figure 3(c)), as shown in Figure 1(c). The air temperature in the tunnel indicated a steady value, ranging from 30.5°C to 31.4°C, without any significant differences from before and after passage of the tunnel, whereas the road-surface temperature dropped with a maximum difference of 25.5°C (Figure 3(d)). The high variability of road-surface temperature in the entrance zone may be attributable to roadside trees and tollgate structures. It is notable that the differences between road-surface and air temperatures inside the tunnel are almost zero. This phenomenon can be interpreted as a result of additional thermal environments due to the high traffic volume, short tunnel length (1.3 km), and lack of ventilation facilities.

3.3. Impact of road-surface materials and water-sprinkling

Surface temperatures are largely affected by the type of material used on the surface (Guan 2011). These surface materials are generally composed of concrete, asphalt, and brick, which absorb and store radiation during the day and slowly release heat during the night (Buyantuyev and Wu 2009). In this regard, road observations by using the MOVE platform are needed, because tracking of road-surface material in actual urban environments is rather important. Therefore, the field measurements based on MOVE were conducted at two road spots with different types of material during
the warmest time of heat-wave days in the Gangnam area. First, the darker-colored asphalts were newly paved at the crossroad spot (around 0529 UTC) of Hakdong station, and second, iron plates were installed at the construction spot of Gangnam station (around 0703 UTC). For intercomparison at an adjoining place, lighter-colored asphalts and general road were selected as consecutive road spots of darker-colored asphalts and iron plates, respectively. These observation sections are displayed in Figure 1(b).

Figure 4 shows box plots indicating the percentiles (1st to 99th) of road-surface and air temperatures for each section obtained with the MOVE data, and Table 1 summarizes their statistical results. There were significant differences in road-surface temperature between all of the materials. The road-surface temperature in the section of darker-colored asphalts was relatively higher than that of lighter-colored asphalts, with differences of 6.8°C and 7.0°C in mean and median, respectively (Figure 4(a)). These results confirm that the color of asphalts affects road-surface temperatures by affecting the albedo of a material (Sailor 1995; Pomerantz et al. 2000; Guan 2011). However, the air temperature above both materials did not mimic the feature shown in road-surface temperature (Figure 4(b)). The mean value (34.2°C) of air temperature in the lighter-colored asphalts section was slightly higher than that in the darker-colored asphalts section, which indicates that the ambient air temperatures above the lighter-colored asphalts section may be warmer than that of the darker-colored asphalts section, as more heat convection occurs over lighter-colored asphalts due to a lower heat storage capacity and higher albedo on the surface (Guan 2011).

In addition, air temperatures were more variable in both lighter- and darker-colored asphalts. Here, we suggest a statistical index, relative variability (RV), which can be interpreted as a normalized interquartile range. The RV of a certain variable (x) is defined as the ratio of $(x_{75\%} - x_{25\%})/x_{50\%}$ where $x_{y\%}$ denotes the y percentile of x. Especially in darker-colored asphalts, the RV of air temperature was 0.041, which was 1.6 times greater than that of surface temperature at 0.025 (Table 1). The air temperature variations above darker-colored asphalts were more variable since ambient air temperatures are affected by solar absorption, surface emissivity and convection depending on heat storage capacity.

On the other hand, the differences in both the mean and median of road-surface temperature between general road and the iron plate section were 10°C, and the RV value (0.004) of that temperature in the iron plate section was smallest (Figure 4(a) and Table 1). Furthermore, air temperature also tended to be higher in the iron plate section than that in the general road section in terms of the mean (35.1°C) and median (35.3°C) (Figure 4(b) and Table 1). These differences are determined by ground material types, and the iron plate with its high thermal conductivity could have affected air temperatures to be warmer.

We further investigated the impacts of water-sprinkling in the section between Maebong- and Dogok-crossroad (between 0740 to 0744 UTC). The results are presented as box plots in Figure 4(c,d), and

![Figure 4](image-url)

**Figure 4.** Box plots (1%, 25%, 50%, 75%, and 99%) of (a, c) road-surface and (b, d) air temperatures for (a, b) material types and (c, d) water-sprinkling in the Gangnam area (marked with a rectangle in Figure 1(b)). The red lines and markers denote median and mean values, respectively.
Table 1. Statistics of road-surface and air temperatures for each section by material type and water-sprinkling in the Gangnam area on 16 August 2018. Units are °C apart from RV, which is dimensionless.

| Section       | Lighter asphalt | Darker asphalt | General road | Iron plate | Without water-sprinkling | With water-sprinkling |
|---------------|-----------------|----------------|--------------|-----------|--------------------------|----------------------|
|               | Sfc. temp. | Air temp. | Sfc. temp. | Air temp. | Sfc. temp. | Air temp. | Sfc. temp. | Air temp. | Sfc. temp. | Air temp. | Sfc. temp. | Air temp. |
| Max           | 47.5          | 34.8       | 52.8        | 34.9       | 48.5        | 35.4       | 52.1        | 35.4       | 46.5        | 33.4       | 38.5        | 33.7       |
| 75%           | 45.3          | 34.5       | 52.4        | 34.7       | 41.8        | 34.5       | 51.9        | 35.4       | 45.3        | 33.3       | 36.4        | 33.4       |
| Mean          | 44.6          | 34.2       | 51.4        | 34.1       | 41.7        | 34.3       | 51.7        | 35.1       | 45.1        | 33.2       | 36.4        | 33.2       |
| Median        | 44.9          | 34.2       | 51.9        | 34.5       | 41.8        | 34.2       | 51.8        | 35.3       | 45.0        | 33.2       | 36.3        | 33.3       |
| 25%           | 44.6          | 33.9       | 51.1        | 33.3       | 41.0        | 34.1       | 51.7        | 35.1       | 44.7        | 33.1       | 36.1        | 33.1       |
| Min           | 37.8          | 33.6       | 46.9        | 32.6       | 37.2        | 33.3       | 49.9        | 34.2       | 44.3        | 32.8       | 34.4        | 32.5       |
| RVₚ           | 0.016         | 0.018      | 0.025       | 0.041      | 0.019       | 0.012      | 0.004       | 0.008      | 0.013       | 0.006      | 0.008       | 0.009      |

detailed statistics are also summarized in Table 1. As expected, significant differences in road-surface temperature were noted between those within and outside the water-sprinkling section (Figure 4(c)). The mean and median values of surface temperature in the water-sprinkling section, 36.4°C and 36.3°C, respectively, were lower by about 8.7°C (19%) than those outside the water-sprinkling section (Table 1). However, air temperatures in both sections have similar mean and median values, ranging from 33.2°C to 33.3°C (Figure 4(d) and Table 1). The ambient air temperatures in the water-sprinkling section were higher, at values of 33.7°C (maximum) and 33.4°C (75th percentile), than those outside the water-sprinkling section, since they have a higher heat release rate as incoming solar energy is balanced by evaporative cooling (the latent heat flux), rather than the ground radiating heat (the sensible heat flux) (Rasmijn et al. 2018). A notable attribute of this observational analysis is that water-sprinkling seems to be not very effective in reducing air temperature over urban roads. Certainly, further investigations are required for better insight into the influence of water-sprinkling.

4. Summary and discussion

In this study, we used intensive observations to investigate the urban road-surface and air temperatures for a heat-wave episode that occurred on 16–17 August 2018 in Seoul. For the purpose of comparing urban roads with different local features under similar synoptic conditions, we divided the survey route into two sections: areas south (Gangnam) and north (Gangbuk) of Han River, Seoul. A MOVE dataset, with high spatial and temporal resolutions, was used to understand the environmental characteristics of those temperatures at the urban microscale in a hot summer season.

First, we analyzed the relationships between road-surface temperatures and urban environmental characteristics, mainly focusing on the screening effect in Gangnam. We discovered that the road-surface temperatures in the east–west section were higher than those in the south-north section, which is consistent with the distribution of solar radiation. From the 3D map view, we considered that the road-surface temperatures in the section where the difference between road-surface and air temperatures is smallest were affected by screening due to surrounding buildings. Our findings indicated that the magnitude of urban road-surface temperature is mainly caused by differences between sun-exposed and shading sections due to the arrangement of high-rise buildings associated with the solar elevation and azimuth. In order to investigate the variations of road-surface and air temperatures according to the topography, we performed an anomaly analysis using the dataset of road observations in the Gangbuk area. The results showed that the road-surface temperature is associated with topographical features, whereas there were no significant characteristics of the relationship between air temperature and topography. In addition, in the section of Namsan3 tunnel, the differences between road-surface and air temperatures were almost zero, which may be attributable to the additional thermal environments, such as high traffic volume and lack of ventilation facilities.

To identify the impact of road-surface materials and water-sprinkling, further examinations were carried out at three different road spots in the Gangnam area: Hakdong station, Gangnam station, and Maebong-Dogok section. The road-surface temperature in the section of darker-colored asphalts was higher than that of lighter-colored asphalts, with a mean difference of 6.8°C; whereas, in darker-colored asphalts, the mean value (34.1°C) of air temperature was slightly lower than that of lighter-colored asphalts, with relatively high variability (RV of 0.041), which indicates that ambient air temperatures seem to be strongly controlled by the solar absorption, surface emissivity and convection. Both surface and air temperatures in the iron plate section were higher than those in the general road section, with mean differences of 10°C and 0.8°C, respectively. Finally, during the water-sprinkling period,
the road-surface temperature was cooled by about 8.7°C (19%) compared to that without water-sprinkling, but there was no significant change in air temperature.

However, it should be noted that this research has a few limitations. The road-surface and air temperatures vary in complex environments, like an urban area. Thus, it is too difficult to describe using a quantitative or statistical method. We were also unable to address various environmental indices or meteorological factors that are known to affect these temperatures, such as the urban canopy layer, traffic volume, surface emissivity, wind, relative humidity etc. Since the current analysis is limited to urban roads only, it is also necessary to examine the characteristics of road-surface temperature for suburban roads or highways. In the end, the integration of numerical prediction models, roadside automatic weather stations and RWISs, as well as MOVE observations, is required to provide better thermal mapping information.

This study emphasizes the relationship between actual road observations based on a MOVE platform and environmental characteristics in an urban area on heat-wave days. In addition, our findings will assist planners and decision makers determining policy priorities (e.g. planting urban trees and water-spraying) to mitigate heat waves with regard to road-surface temperature, and provide reliable local-scale information on urban road risks. Although this approach has a couple of limitations, the current results could be used practically to improve road-surface temperature prediction models for civil engineers or road managers. Additionally, we plan to utilize a MOVE platform in order to investigate characteristics of urban road-surface and air temperatures in night environments, as addressed by Svensson and Eliasson (2002). The next challenge will be to demonstrate the influence of tunnel internal temperature and the need for appropriate choices of surface materials to understand the damage characteristics of road tunnel fires, as highlighted by Brahim et al. (2011) and Lai, Wang, and Xie (2016).

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