A pilot study exploring the effect of vehicular waste heat on personal heat exposure

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Abstract

Understanding the causes of heat in various microclimates in cities is vital to improving human thermal comfort and health in outdoor spaces. This pilot study uses an experimental design to evaluate microclimate heat risk – including ambient air temperature (TA) and wet bulb globe temperature (WBGT) – and approximate personal heat exposure of people 1.5-3.0 meters (5-10 feet) away from idling vehicles. These measurements were taken at a University of Arizona covered parking garage in June 2022 to investigate personal heat exposure attributable to vehicular waste heat while also minimizing the effect of solar radiant heat and wind. We used Kestrel 5400 devices to document the waste heat effects of a fleet of six identical gasoline-powered vehicles on the surrounding microclimate by collecting TA, wind velocity, and WBGT. When compared to the control, as well as comparing a period when engines were not idling, we found a strong correlation between vehicle presence, TA, and WBGT. Specifically, ordinary least-mean square (OLS) modeling shows an additional TA per minute increase of 0.006°C (a 25% increase) per minute when the vehicles are on and idling versus 0.024°C per minute increase that occurs from expected background morning temperatures when the vehicle effect is removed. Until we transition to an electric fleet and increase use of alternative modes of transportation, these findings can help inform how transportation professionals design the built environment and manage traffic and transit during summer months to prevent excessive heat exposure for pedestrians, cyclists, transit riders, and other individuals near idling vehicles.

Introduction

Heat is an increasing climate risk for communities across the world. Extreme heat events are occurring more frequently, are more intense, and are becoming longer in duration due to climate change [1]. Heat wave frequency for cities in the United States (US) has increased from an average of two heat waves per year in the 1960s to an average of six per year in the 2010s [2]. Microclimates, or the climatic conditions in an immediate area, are affected by multiple sources of heating and cooling, including waste heat, land cover, evaporation, evapotranspiration, bodies of water, tree shade, and constructed object shade [3]. Variations in microclimate conditions can exacerbate personal heat exposure risk [3,4], and in response, communities are increasingly planning for heat resilience by using both heat mitigation strategies that reduce urban heat in the built environment and heat management strategies that prepare and respond to chronic and acute heat risk [5,6]. The urban heat island (UHI) effect is attributed to both heat that is absorbed in the built environment and then later released, as well as waste heat [7].

Traditional gasoline-fueled vehicles reflect light, produce emissions, create noise, and generate waste heat that increases heat in microclimates. Waste heat, or anthropogenic heat, is released as a result of energy use from human activities and has been reported to cause a 1.0°C to 4.0°C (1.8°F to 7.2°F) warming in near-surface air temperatures [8]. By better understanding the contribution of vehicular waste heat to microclimates, we can learn more about heat's influence on travel behavior and heat resilience. Personal heat exposure, or the human experience and perception of heat, is foundational to understanding how people perceive and navigate outdoor spaces, including transportation spaces, particularly during warm weather [4,9]. Studies have explored the effects of buildings and green space on their respective microclimates, but an understudied area of work in planning is the effect of vehicular waste heat on microclimates. This is likely due to the mobile nature of vehicles, the variation in their operation, and the complexity of environmental conditions, resulting in rapid changes in air temperature, solar radiation, and air movement [10].

The few studies that have addressed vehicular waste heat have hinted at a large impact on the regional UHI. Waste heat loads tend to be largest during morning and evening peak travel times. Analyzing the effects of vehicular, building, and human metabolism heat in the summer suggests that heat from vehicles accounts for 47% to 62% of the total heat generated [11]. Yet little research examines how vehicle waste heat reduces pedestrian perceived comfort, a factor often cited in both traffic safety [12] and green facility contexts [13]. While guidelines to provide systematic overviews of microclimate field measurements exist to support research procedures in urban areas, more studies are needed to provide frameworks in various climates and diverse conditions [14].

Heat severity is also inequitable felt. For instance, heat severity is higher in previously redlined communities and those with higher proportions of minority or lower-income households [15,16]. Yet, the effect of vehicles themselves on ground-level TA and personal heat exposure of different types of people – pedestrians, cyclists, and fast-food workers or traffic flaggers – is poorly documented [17]. In addition to highlighting how little we understand about active travel and heat, models by Karner, Hondula, and Vanos [17] suggest that low-income individuals and other vulnerable populations are more likely to rely on non-motorized travel, increasing their potential heat exposure.

Thus far, there is little in the literature regarding the direct effects of the presence of vehicles on microclimates and personal heat exposure. Lindberg et al. [18] identified waste heat – released through fixed sources such as cooling and lighting as well as the transportation system – as one of the factors affecting the outdoor thermal environment [18]. Thus, it is important to incorporate vehicular waste heat contributions to temperature changes in urban areas. In addition, Hart & Sailor [19] demonstrated that TA near major roadways are the warmest in the area due to the impervious nature of the roads and increased building and waste heat emissions [19]. To date, few studies capture the direct effect of vehicular waste heat on personal heat exposure. As Keith, Meerow, and Wagner [5] found, sixty percent of heat planning research was published within the last five years, but the majority focuses on modeling or mapping heat, suggesting that there is more to be explored through natural and field experiments.

A notable exception to the understudied area of waste heat research in the field is Girgis, Elariane, and Elrazik [20] who documented the range of temperature changes caused by idling buses and domestic air conditioning condensers through the use of infrared cameras. Air conditioners increased the TA by almost 1.0°C (1.8°F). Overall, the presence of idling buses increased the surrounding TA from 1.0°C to 4.0°C (1.8°F to 7.2°F) due to the heat emitted from idling buses and the associated reduction in air velocity [20]. While Girgis, Elariane, and Elrazik [20] addresses the direct effect of large vehicles on TA, it does not identify the effect on WBGT, a common way of identifying how various temperatures and external factors such as wind and perspiration feel to the human body.

This pilot study explores the impact of traditional gasoline-powered vehicular waste heat on the microclimates near vehicles – spaces that non-vehicular travelers often occupy. Our research seeks to answer how the presence of traditional gas-fueled vehicles influences personal heat exposure. This experiment was designed to quantify how much the presence of a fleet of idling gasoline-fueled vehicles influences TA and personal heat exposure – measured using WBGT – while controlling for several other factors in a covered parking garage. This design includes two primary comparisons: (a) vehicles idling versus not idling and (b) the presence (vehicle-adjacent) or absence (control) of vehicles. A study completed at the University of Arizona's Point of Distribution (POD) for COVID-19 vaccinations in Tucson, Arizona laid out the groundwork for the personal heat exposure methodology used in the current study, such as instrumentation, type of data collected, and heat-risk metrics [21]. Another study following a similar methodology modified instrument placement and collected TA, WBGT, wind speed, and traffic entry and exit data at the same Tucson POD, focusing on sites 1.7-2.0 meters (5.5-6.5 feet) away from vehicular traffic at the three highest risk locations [22]. This analysis suggested a vehicular waste heat effect, even though the variation in heat measured was high due to natural experiment factors [22].

We hypothesized that the presence of vehicles would increase ambient air temperatures (TA) and wet bulb globe temperatures (WBGT), increasing personal heat exposure in nearby microclimates. This paper reports these findings, provides a framework for future similar microclimate measurements, and identifies ways to understand and mitigate vehicular waste heat effects on personal heat exposure.

Materials and Methods

Study area and sites

We collected data for this study in the University of Arizona (UArizona)'s South Stadium Garage in Tucson, Arizona on June 4, 2022, from 8:00 AM through 10:00 AM. This study expands on methodology reported from the UArizona COVID-19 vaccination POD in April 2021 [21] and expands on experiment design ideas documented in a connected presentation [22]. For this experiment, researchers blocked off the entrances to the first floor of the South Stadium Garage and located the experiment in an area that would reduce temperature variation from wind, other vehicles, and the sun.

We collected data using nine Kestrel 5400 devices located throughout the parking garage. Fig 1 shows the location of the Kestrels and the vehicle fleet during data collection on June 4, 2022. The vehicle fleet consisted of six Chevrolet Malibu vehicles, a type of mid-size sedan, from the UArizona fleet. Five vehicles were 2020 models, and one was a 2019 model; all were equipped with traditional gasoline-fueled engines. We used the dimensions of the vehicles (approximately 4.9 meters by 1.8 meters [15 feet by 6 feet]) to create vehicle location guidelines of 6.7 by 3.7 meters (22 feet by 12 feet) boxes, marked in Fig 1 in three columns (columns 1, 2, and 3) and two rows (rows A and B) with additional buffer spaces. These measurements are also shown in Fig 1.

Fig1. Map of Site with Locations Marked

Control Kestrels (West, West 2, and East) were placed away from the vehicle fleet, but within the garage to maintain similar conditions, such as similar ground cover and airflow. These three control Kestrels were set up to determine how effectively each Kestrel acted as a control. Both West Kestrels are directly next to each other to check the accuracy of the two instruments. They were accurate to one another, with the average difference between the instruments recorded as 0.0056°C (0.01°F), with a standard deviation of 0.1°C (0.18°F), giving us a measure of our instrument consistency. By reviewing wind roses and summary statistics, we found that the west end of the garage was exposed to more inconsistent wind speeds, while the east end had more similar microclimatic conditions to the vehicle test site. Thus, when we refer to the control from this point on, we are referring to East Kestrel.

Tucson is in a semi-arid, desert environment characterized by low humidity and hot temperatures during the early summer months. The Tucson International Airport recorded an average June 2022 TA of 31.7°C (89.1°F) with 5.8 millimeters (0.23 inches) of precipitation over the month [23]. On the morning of June 4th, the airport TA averaged 27.8°C (82.0°F) between 7:00 AM and 9:20 AM, the time of active data collection [24]. This was slightly lower than the Kestrel 5400 control on site, which recorded an average TA of 28.1°C (82.5°F) at that same time. Average wind speed recorded at the airport was 9.7 kph (6.0 mph); the site's control Kestrel measured an average wind speed of 0.1 kph (0.07 mph). There was no precipitation recorded on the data collection day.

Data collection

We used the Kestrel 5400 devices to collect ambient air temperature (TA), wet-bulb globe temperature (WBGT), and wind speed for this analysis. Data was recorded once every ten seconds during the study period.

Once we set up all Kestrels and vehicles (see Fig. 1), we waited 15 minutes to allow the Kestrels to normalize to background temperatures and began our experiment at 7:15 AM. Vehicles were then turned on at 7:35 AM (within approximately 15 seconds of each other). Each vehicle had air conditioning set to its max value but was otherwise left idling for the next 50 minutes. After 50 minutes had passed, the research team turned the vehicles off at 8:20 AM. Vehicles remained present, but with their engines off for the next hour. The experiment ended at 9:20 AM. We call these three periods (a) Vehicles Off, (b) Vehicles On, and (c) Cool Off, respectively throughout our analysis.

Full descriptive statistics for our data are provided in Table 1. Our descriptive statistics demonstrate the averages and standard deviations for measurements collected using the nine Kestrel 5400 instruments.

Table 1 Descriptive Statistics of Data Collected

		Vehicle-Adjacent Kestrels						Control Kestrels		
Location:		1A	1B	2A	2B	3A	3B	East	West	West2
Ambient Air Temperature (TA) (°C)	Mean	28.30	28.33	28.30	28.29	28.26	28.14	28.04	27.70	27.71
	St. Dev.	0.89	0.79	0.77	0.77	0.73	0.71	0.68	0.90	0.89
Wet Bulb Globe Temperature (WBGT) (°C)	Mean	19.51	19.62	19.40	19.70	19.60	19.56	19.56	18.82	*NA*
	St. Dev.	0.50	0.43	0.40	0.44	0.37	0.36	0.35	0.56	*NA*
Wind Speed (m/s)	Mean	0.35	0.15	0.15	0.03	0.03	0.05	0.07	0.51	0.56
	St. Dev.	0.38	0.26	0.27	0.12	0.13	0.16	0.20	0.38	0.48

Notes:
Each Kestrel collected 751 observations, once every 10 seconds, summarized here. Each minute (with six 10-second observations) was averaged before the regression analysis was conducted. *NA*: Not available.

Analysis

We downloaded Kestrel 5400 data as a .CSV file and imported into the statistical programming software, R, for analysis. We analyzed data at the raw 10-second intervals and at one-minute averages (e.g., averaging six 10-second observations), although only the results for the minute averages were used in regression analysis in this paper. First, we examined the temperature measurements graphically, paying attention to the general morning warming temperature trend seen in the control and then comparing that trend with the vehicle-adjacent observations.

Second, we tested our research hypothesis using an ordinary least-mean square (OLS) linear regression. We created models for two different dependent variables: TA and WBGT, segmenting the data by vehicle-adjacent observations and control observations, for a total of four models. In this regression analysis, we control for wind speed (meters per second). We also include two dummy variables for the "Vehicles On" and "Cool Off" time periods (compared with the initial "Vehicles Off" base case). The clear linear warming trend consistent with increasing morning temperatures (7:15AM-9:20AM) suggested we add time elapsed as an independent variable instead of employing additional time series techniques. For the vehicle-adjacent models, we also included a dummy variable for distance from vehicle (Row A [closest, 1.5m or 5ft] = 0; Row B [furthest, 3.0m or 10ft] =1).

We expected to see a similarly identified vehicle effect in WBGT and in TA because of the controlled effects of radiant heat and wind speed. We hypothesized that the anticipated vehicle-caused heat in the surrounding area would be a result of waste heat; thus, these changes would be equally captured in both measurements. During our tests, we expected to see WBGT and TA significantly increase at a higher rate when vehicle engines were on, and with the presence of vehicles. We anticipated this difference would be detected at a lagging rate because WBGT is also slower to respond to changes in the environment due to the time it takes for the interior of the bulb in the instrument to warm. We hypothesized that our control, set up within the garage on the same paved ground cover, but at a slightly lower elevation due to the subtle slope in the parkinge garage, would record consistently lower TA and WBGT.

Results

In this pilot study, we used Kestrel 5400 devices to document the potential waste heat effects of a fleet of six gasoline-powered vehicles on the surrounding microclimate and personal heat exposure by collecting TA, wind velocity, and WBGT. The results from the four regressions are provided in Table 2 and explored further in this section. Explained variation, or goodness-of-fit, was much higher for TA (control adjusted-R2: 0.982, vehicle-adjacent: 0.944) than for WBGT (control adjusted-R2: 0.863, vehicle adjacent: 0.864). This is likely because the WBGT measurement includes the radiant heat from both vehicles and the built environment, the latter which is slower to respond to changes in microclimates than TA.

Table 2 Regression Results for Four Models of Ambient Air Temperature (A, B) and Wet Bulb Globe Temperature (C, D) at Two Locations (Control and Vehicle-Adjacent)

Model:	A			B			C			D		
Dependent variable:	Ambient Air Temperature (°C)			Ambient Air Temperature (°C)			Wet Bulb Globe Temperature (°C)			Wet Bulb Globe Temperature (°C)		
Location	Vehicle-Adjacent			Control			Vehicle-Adjacent			Control		
Independent Variables:	Coef	Confidence Interval	p-value	Coef	Confidence Interval	p-value	Coef	Confidence Interval	p-value	Coef	Confidence Interval	p-value
Intercept	26.717	26.651 – 26.784	**<0.001**	26.683	26.599 – 26.767	**<0.001**	18.611	18.554 – 18.668	**<0.001**	18.776	18.658 – 18.895	**<0.001**
Wind (m/s)	-0.053	-0.115 – 0.009	0.094	-0.095	-0.205 – 0.015	0.09	-0.173	-0.226 – -0.120	**<0.001**	-0.452	-0.606 – -0.297	**<0.001**
Kestrel Location												
Row A (Closest)			Base Case			Base Case			Base Case			Base Case
Row B (Furthest)	-0.036	-0.063 – -0.008	**0.01**				0.107	0.084 – 0.130	**<0.001**			
Time Period												
Vehicles Off			Base Case			Base Case			Base Case			Base Case
Vehicles On	0.102	0.003 – 0.202	**0.044**	0.281	0.157 – 0.406	**<0.001**	0.086	0.001 – 0.171	**0.048**	0.174	-0.001 – 0.349	0.051
Cool Off	0.516	0.393 – 0.639	**<0.001**	-0.071	-0.235 – 0.092	0.389	1.221	1.116 – 1.326	**<0.001**	0.984	0.754 – 1.214	**<0.001**
Time Elapsed (T_elapsed)	0.024	0.019 – 0.030	**<0.001**	0.032	0.025 – 0.040	**<0.001**	0.015	0.010 – 0.020	**<0.001**	0.024	0.014 – 0.035	**<0.001**
Interacted Time Elapsed and Time Period												
T_elapsed * Vehicles-Off			Base Case			Base Case			Base Case			Base Case
T_elapsed * Vehicles-On	0.006	0.000 – 0.012	**0.038**	-0.014	-0.022 – -0.006	**0.001**	0.005	-0.000 – 0.010	0.073	-0.011	-0.022 – -0.000	**0.048**
T_elapsed * Cool-Off	-0.007	-0.013 – -0.001	**0.021**	-0.011	-0.019 – -0.003	**0.005**	-0.015	-0.020 – -0.010	**<0.001**	-0.023	-0.034 – -0.012	**<0.001**
Observations			756			126			756			126
Adjusted R2			0.944			0.982			0.864			0.863

Date of data collection: June 4th, 2022; **Site**: University of Arizona South Stadium Garage; **Unit of analysis**: one-minute average observations between 7:15 AM through 9:20 AM

p-value **bolded** when < 0.05

After we control for the location of the Kestrels and the idling engines, we found the TA increased at a significant ($p < 0.001$) rate of 0.024°C and 0.032°C for the vehicle-adjacent and control Kestrels, respectively, throughout the entire period of data collection. This can be interpreted as the per minute temperature increase throughout the morning within the garage, which we refer to as the background morning temperature. For WBGT, we found this significant ($p < 0.001$) rate to be 0.015°C and 0.024°C for vehicle-adjacent and control Kestrels, respectively. For the vehicle-adjacent Kestrels, the observations in "Row B" (3m) observed statistically lower ambient temperatures (-0.036°C, $p < 0.05$) and higher WBGT temperatures (0.107°C, $p < 0.001$) compared with the "Row A" (1.5m) Kestrels. This again may suggest WBGT may pick up on the radiant temperatures from the idling/cooling vehicles that do not impact TA. Given that WBGT is a more appropriate proxy for human thermal comfort, this suggests that the impact of radiant heat from idling vehicles may be more strongly felt by humans than observed by ambient temperature measurements. This may also be attributed to radiant heat that may be reflecting off a wall on the north side of the experimental area, just beyond Row B of Kestrels.

The primary purpose of this pilot study was to quantify the additional temperature increase that vehicles emit as waste heat; this was measured by comparing the rate increase in temperature during the Vehicles On and Cool Off time periods, compared with the initial Vehicles Off time period. We compare these changes by both the time period dummy variables as well as the interaction of these time periods with the minute-by-minute time elapsed.

For the vehicle-adjacent Kestrel model (Table 2, Column A), when vehicles are idling (from 7:35 AM to 8:20 AM), the TA was approximately 0.1°C ($p < 0.05$) greater than when vehicles were off, in addition a significant increase in TA over time by 0.006°C per minute ($p < 0.05$). During the "Cool Off" period, the vehicle-adjacent Kestrels measured a 0.516°C increase in overall TA with a slightly lower increase in overall TA per minute compared to the "Vehicle Off" period (-0.007°C, $p < 0.05$).

For WBGT at the vehicle-adjacent kestresl (model C), the Vehicles On period and Cool Off period were 0.086°C ($p < 0.05$) and 1.221°C ($p < 0.001$) greater, respectively, compared with the Vehicles Off period. The higher temperatures during the Cool Off period may reflect the lagged effect of an aggregated index measure of temperature. When interacting the time elapsed in minutes with the two time periods, the Vehicles On period resulted in a 0.005 °C greater rate of change in WBGT over time with marginal significance ($p < 0.1$). Additionally, the rate of change for the Cool Off period was 0.015°C less ($p < 0.001$) than the base case. Since the morning temperatures were still increasing by 9AM, this suggests that the WBGT may not be as sensitive to changes in temperature as the aggregated index nature of the variable would suggest. WBGT is less sensitive to change, particularly without changes in direct radiation heat from the sun, strong winds, and humidity; we designed the experiment to minimize these effects (e.g., block sun and wind via the parking garage and selecting a day with low humidiy). The greater increase in WBGT for vehicle-adjacent Kestresl during the Cool Off suggests perhaps the increase in radiant temperature from the vehicles after having been on resulted in slightly higher temperature impacts for WBGT (compared with TA) during the Cool Off period.

When comparing the measurements at the control Kestrel for TA and WBGT (model B and D), TA was significantly greater during the Vehicles On period by 0.28°C ($p < 0.001$) and WBGT was marginally significantly greater by 0.17°C ($p < 0.1$) compared with the initial Vehicles Off period. While there is no difference in TA between the Cool Off and the initial Vehicles Off period, the WBGT was nearly 1.0°C warmer ($p < 0.001$) during the Cool Off period. For both TA and WBGT at the control location, the rate of change in temperature per minute was both significant and less during the Vehicles On period (TA: -0.01°C, p

<0.01; WBGT: -0.01°C, $p < 0.05$) and Cool Off periods (TA: -0.01°C, $p <0.01$; WBGT: -0.02°C, $p < 0.001$). Given that the East control used in this analysis was behind the idling vehicles, albeit significantly farther than the vehicle-adjacent vehicles, it is feasible that the increase in TA during the Vehicles On period may be a result of the exhaust from the vehicles pointing in the direction of the control. Alternatively, the positive difference in WBGT at the control location during the Cool Off—roughly 80% of that measured at the vehicle-adjacent location—may have increased due to the radiant temperatures of the vehicles measured at a further distance.

To depict the regression results graphically, we used each of the four models to predict the average expected temperatures for from each of the four regressions assuming no wind speed at the 1.5m ("Row A") vehicle-adjacent location, and then we graphed these results against the one-minute observations (see Figs. 2-5). We also observe some outliers in the graphic towards the end of the collection period (after 9:00AM), particularly in the WBGT models (Fig 4 and 5). We believe it is related to a slight increase in wind speed. We selected this parking garage location because it was a semi-enclosed space to allow for outdoor temperature increases while minimizing radiant heat from the rising sun as well as wind. Wind speed is both marginally significant and negatively related to TA (models A and B), and it is significantly and negatively related to WBGT (models C and D). The slightly greater statistical significance and effect size for wind and WBGT is an expected result because WBGT incorporates wind as well as humidity and radiation within the index calculation. A one meter per second increase in wind speed leads to a 0.17°C drop in WBGT in vehicle-adjacent Kestrels and a 0.45°C in WBGT in the control model.

Fig 2. Average Ambient Air Temperature (in degrees F) Across Time for East Control

Fig 3 Average Ambient Air Temperature (in degrees F) Across Time for Vehicle-Adjacent Kestrels

Fig 4. Average Wet Bulb Globe Temperature (in degrees F) Across Time for East Control

Fig 5. Average Wet Bulb Globe Temperature (in degrees F) Across Time for Vehicle-Adjacent Kestrels

Discussion and conclusion

Overall, the impact of vehicles on transportation systems; the impact of transportation systems to the UHI effect, microclimates, and personal heat exposure; and the interaction of all of these on non-vehicular travel behavior is poorly understood. This pilot study contributes to a better understanding of the relationships between gasoline-fueled vehicular waste heat and microclimates immediately adjacent to idling vehicles using TA and WBGT. Additionally, the experiment findings support our hypothesis that vehicle waste heat can influence personal heat exposure within 1.5-3.0 meters of idling vehicles. This was demonstrated most clearly in the vehicle-adjacent Kestrel by showing a TA increase of 0.006°C per minute for a total increase of 0.032°C per minute when the vehicles are on and idling versus 0.024°C per minute increase that occurs from expected background morning temperatures when the vehicles are off—roughly a 25% increase in the rate of change in temperatures. Notably, the background morning temperatures for the control TA model show a similar climb throughout (0.032°C per minute).

Our findings demonstrate that both vehicle presence and engine idling can increase personal heat exposure and warrant further study. By understanding the influence of vehicles on personal heat exposure at a human scale, we further inform design and operational strategies to improve the experiences and heat safety of all travelers. For example, to avoid excessive heat risk during warmer periods, signal timing may be reconfigured to prioritize active travelers, minimizing time spent alongside idling vehicles at intersections or during excessive idling periods, such as in construction. Another potential heat exposure solution to help minimize the effects of vehicular waste heat would be cooling buffers, such as lining walkways with trees. Additionally, understanding the cool-off period and conditions during which it occurs would provide information on how elevated temperatures clear out in areas such as intersections where traffic cycling occurs.

Our results also hint at some temporal questions. Results from this experiment indicate that temperatures near idling vehicles steadily increase at a faster rate, approximately 25% greater in this morning's experiment. Although we arbitrarily cut the time to 50 minutes for the six idling vehicles, our data showed no major signs of stagnation in the rate of temperature increase. Extending the time in future studies could indicate if the rate remains linear or has an asymptotic limit. This would inform situations involving idling cars for hours at a time, such as ports-of-entry, drive-thru restaurants, heavy-traffic arterial roads, and more. Testing other models of vehicles, including older vehicles and vehicles with larger engines, could also help define the range of exposure associated with a fleet.

Personal heat exposure near an idling vehicle is a function of the time spent near the idling vehicle and the length of time the vehicle – or vehicles before it in the same space – has been idling. As a next step, we suggest a sensitivity analysis that uses these TA and WBGT relationships to discover the point at which pedestrian and cyclist heat safety might be of concern. For example, once WBGT exceeds 27°C (80.6°F), precautions should be taken while completing moderate work, such as walking at 5.6 kph (3.5 mph, about average walking speed) while carrying objects [25]. This threshold could be reached quickly while walking to a bus stop with shopping bags near a congested intersection. Furthermore, to better estimate the impact on human thermal comfort, more work is needed to understand at what points heat impacts human psychological and physical systems for different people in different conditions.

Finally, confirming the waste heat of gasonline-powered vehicles has implications for our growing understanding of the UHI effect, given current vehicle fleet compositions. This research demonstrates the contribution of waste heat to a microclimate, as shown by a fleet of six cars powered by gasoline. A large city likely has hundreds of thousands of cars idling at any one time, resulting in a significant additional UHI effect [11]. Transitioning to an electric vehicle fleet or alternative modes of travel (e.g., biking, walking, transit) may reduce carbon emissions and mitigate urban heat by reducing the personal heat exposure of individuals who find themselves along roads with idling cars. Until that transition is complete, the waste heat from vehicles into the surrounding thermal environment is a phenomenon for which planners and engineers should account, plan, and mitigate.

By better understanding the relationship between waste heat and vehicle presence, we can strengthen heat resilience efforts in cities through heat mitigation and management. Thus, we recommend further research to document and understand personal heat exposure for travelers across transportation modes and how vehicles contribute to increasing heat risk.

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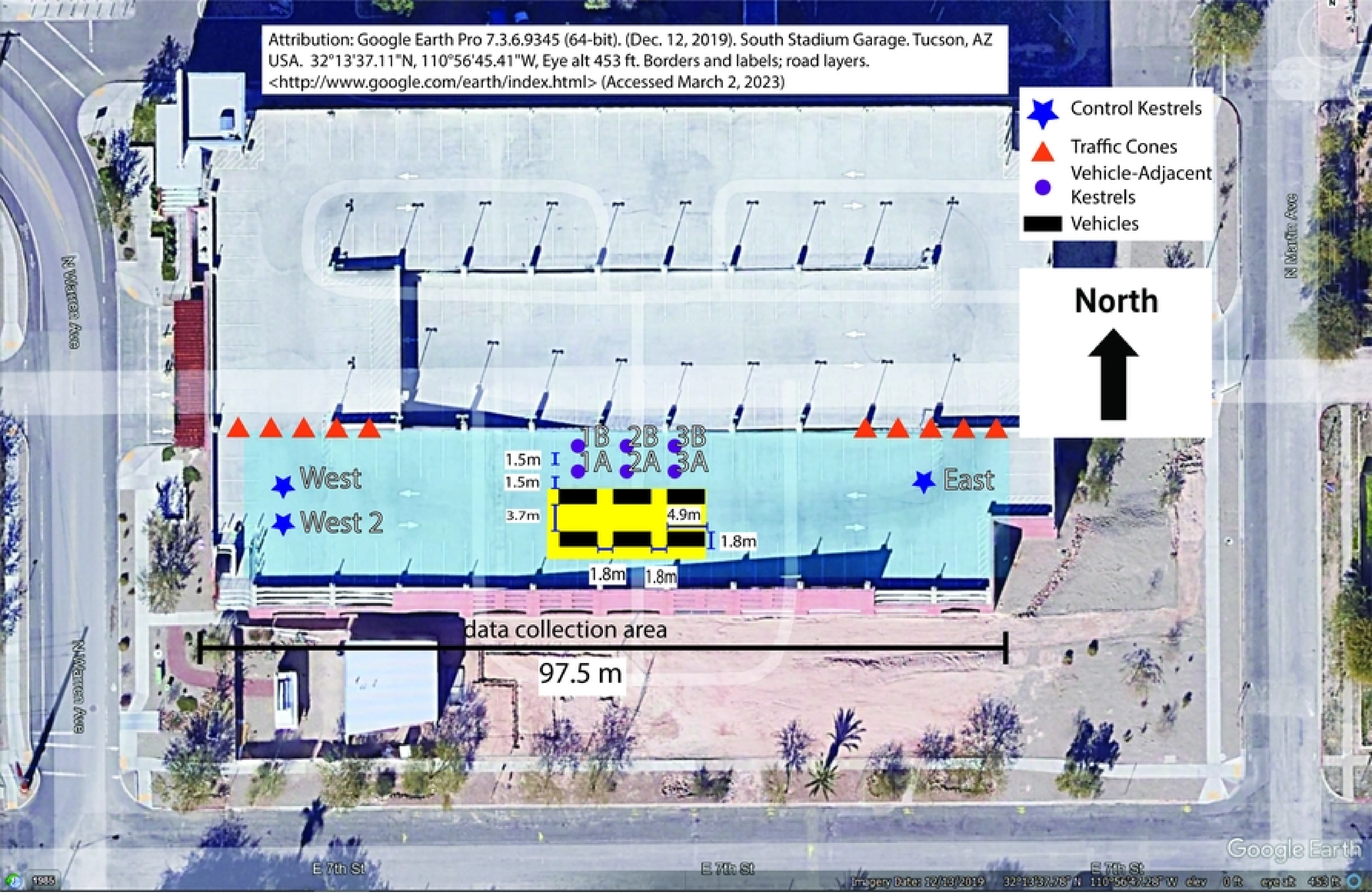
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Control Kestrels
Traffic Cones
Vehicle-Adjacent Kestrels
Vehicles
North
N Warren Ave
N Martin Ave
1B
2B
3B
1A
2A
3A
1.5m
1.5m
West
West 2
East
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data collection area
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Google Earth

Fig 1

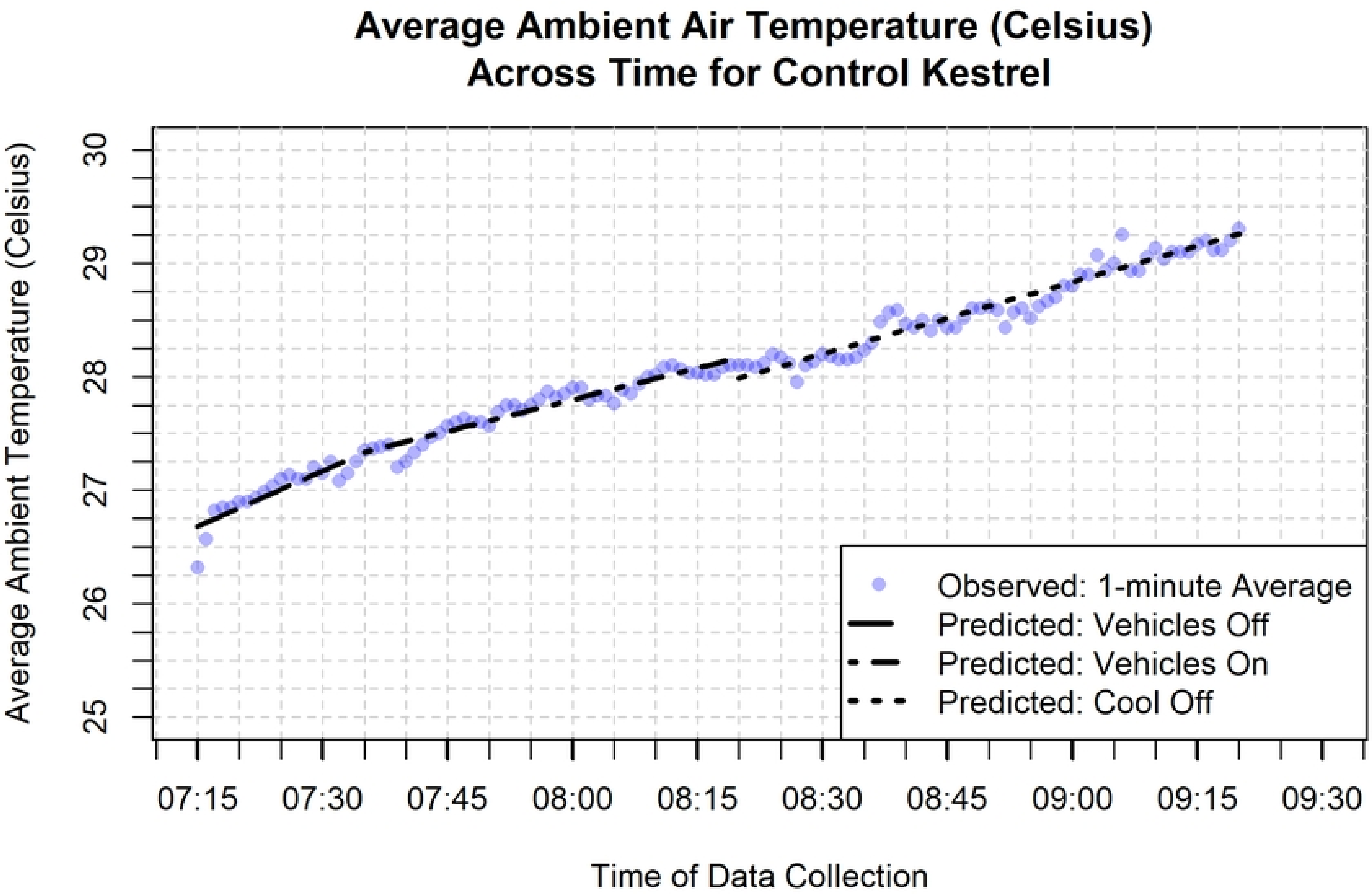
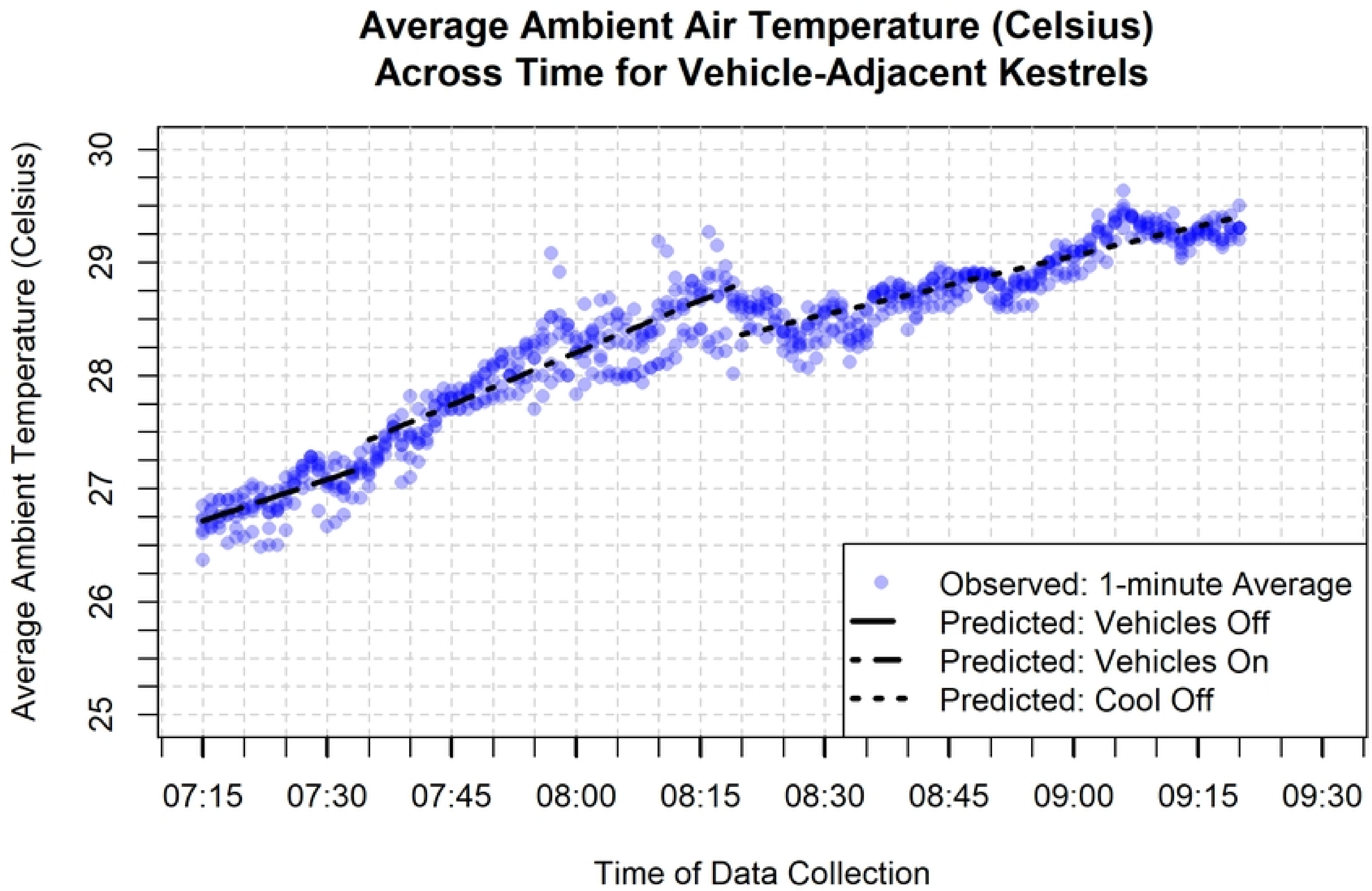

Average Ambient Air Temperature (Celsius)
Across Time for Control Kestrel
Average Ambient Temperature (Celsius)
25
26
27
28
29
30
07:15
07:30
07:45
08:00
08:15
08:30
08:45
09:00
09:15
09:30
Time of Data Collection
Observed: 1-minute Average
Predicted: Vehicles Off
Predicted: Vehicles On
Predicted: Cool Off

Fig 2



Average Ambient Air Temperature (Celsius)
Across Time for Vehicle-Adjacent Kestrels
Average Ambient Temperature (Celsius)
25
26
27
28
29
30
07:15
07:30
07:45
08:00
08:15
08:30
08:45
09:00
09:15
09:30
Time of Data Collection
Observed: 1-minute Average
Predicted: Vehicles Off
Predicted: Vehicles On
Predicted: Cool Off

Fig 3

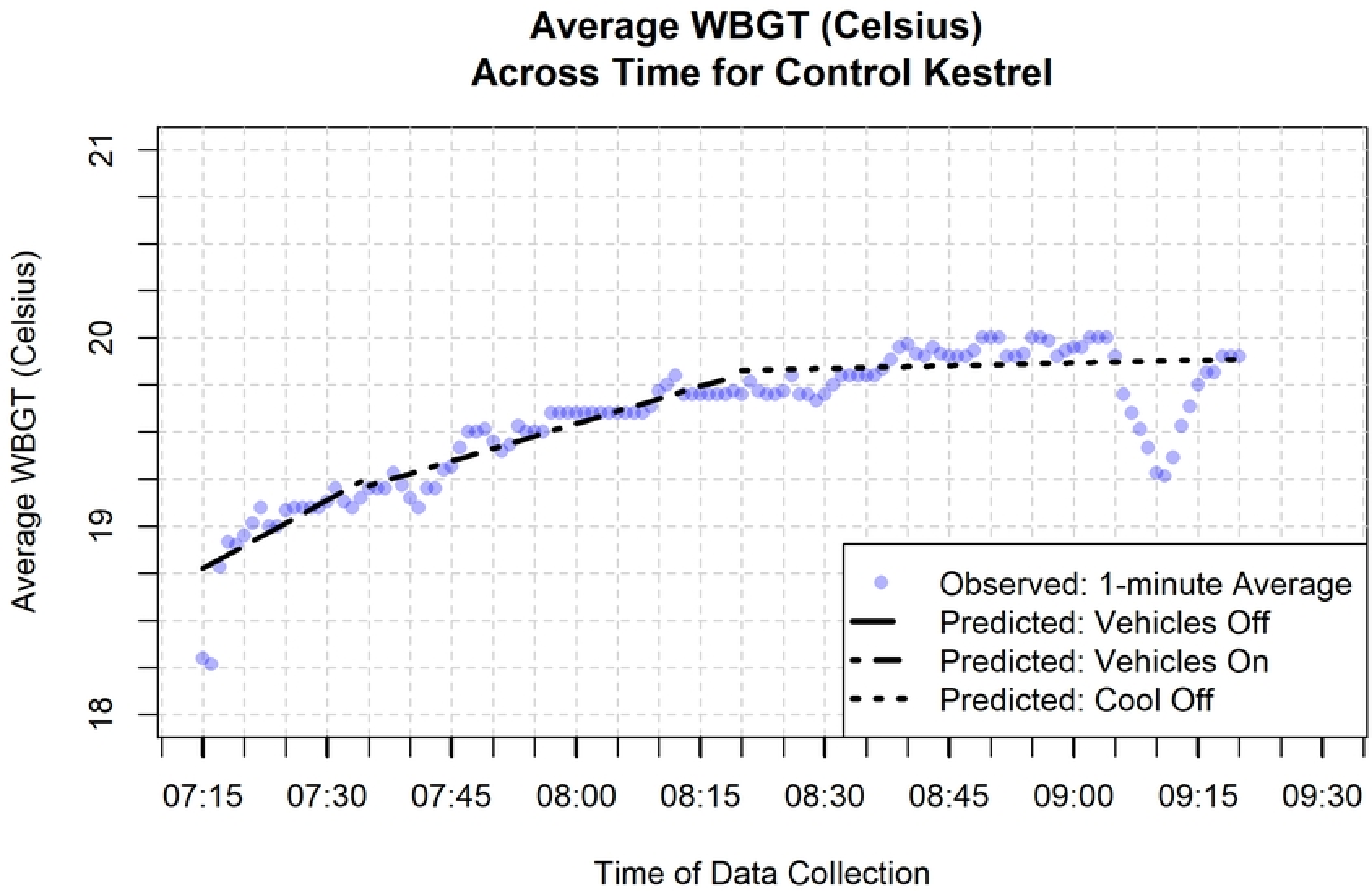

Average WBGT (Celsius)
Across Time for Control Kestrel
Average WBGT (Celsius)
21
20
19
18
07:15
07:30
07:45
08:00
08:15
08:30
08:45
09:00
09:15
09:30
Time of Data Collection
Observed: 1-minute Average
Predicted: Vehicles Off
Predicted: Vehicles On
Predicted: Cool Off

Fig 4

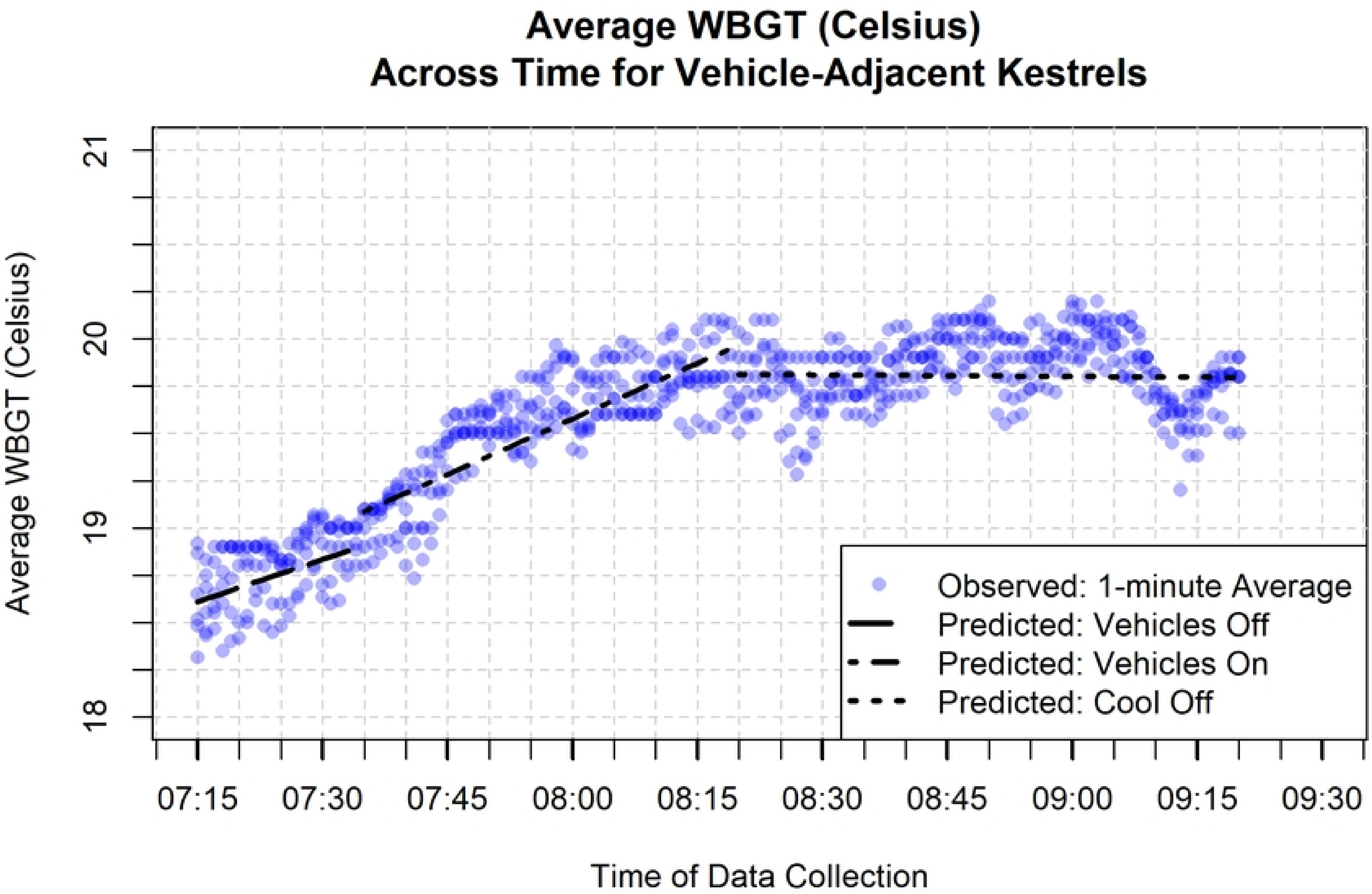

Average WBGT (Celsius)
Across Time for Vehicle-Adjacent Kestrels
Average WBGT (Celsius)
21
20
19
18
07:15
07:30
07:45
08:00
08:15
08:30
08:45
09:00
09:15
09:30
Time of Data Collection
Observed: 1-minute Average
Predicted: Vehicles Off
Predicted: Vehicles On
Predicted: Cool Off

Fig 5