Urban Climate 61 (2025) 102429

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Ambient environmental exposures while cycling on a vegetated trail versus the road

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ARTICLE INFO

Keywords:
Air quality
Natural sounds
Anthropogenic noise
Heat stress
Co-exposures
Nature-based solutions

ABSTRACT

Cycling can improve health, yet cyclists in cities may be exposed to hazardous conditions and have limited exposure to nature and its benefits. The purpose of this study was to measure and compare environmental exposures of urban cyclists on a vegetated, gravel trail route separated from cars and a fully paved route on local roads. In September 2021 in Austin, Texas, US, we cycled on the trail and road routes from 7:30–8:30 and 17:30–18:30 on one weekday and weekend day. While cycling, we wore sensors that measured fine particulate matter (PM2.5), total volatile organic compounds (VOCs), sounds, air temperature, relative humidity, light intensity, and geographic location. We used a neural network to distinguish anthropogenic and natural sounds. After time-matching all sensor data, we specified linear mixed effects models to test the association between route type and each environmental exposure, adjusting for afternoons and weekdays. We also used inverse distance weighting in GIS to map spatially continuous estimates of environmental exposures for each cycling trip. Compared to the road route, the trail was associated with higher levels of PM2.5, total VOCs, natural sounds, and relative humidity, and lower levels of anthropogenic sounds, temperature, and light intensity ($p < 0.05$). Mapping illustrated differences in environmental exposures within and between routes by time of day and day of week. Assessing exposures on existing and planned cycling routes may help inform the design of health interventions (e.g., tree planting along routes) in the face of increasing climate-related hazards.

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https://doi.org/10.1016/j.uclim.2025.102429
Received 24 December 2024; Received in revised form 18 March 2025; Accepted 13 April 2025

1. Introduction

In urban areas across the United States (U.S.), only about 1 % of all trips are completed by bicycle (Goel et al., 2022). Increasing the U.S. cycling rate carries health, environmental, and economic benefits. Riding a bicycle is a viable way to engage in physical activity, a behavior that provides both immediate and long-term health benefits (U.S. Centers for Disease Control and Prevention, 2023). The physical activity benefits of cycling have been found to generally outweigh the risks of air pollution, even with higher inhalation and uptake of pollutants while cycling compared to riding a car and other sedentary travel modes (Cepeda et al., 2017; De Nazelle et al., 2017; Tainio et al., 2021). For instance, researchers have estimated in life-years the benefit of increased physical activity (3–14 months gained) due to shifting from car to bicycle in the Netherlands far outweigh the costs of increased inhaled air pollution dose (0.8–40 days lost) and traffic collisions (5–9 days lost) (De Hartog et al., 2010). Furthermore, shifting travel mode from internal combustion engine vehicles to bicycles reduces air pollution, greenhouse gas emissions, and congestion, among other harmful impacts of vehicle use (Pucher and Buehler, 2010).

When cycling outdoors, riders come into direct contact with ambient environmental exposures such as air pollutants, sounds, temperature, and sunlight, which can affect the overall health benefits that cycling can impart. Personal exposure assessments of ambient environmental conditions while cycling have primarily focused on air pollution. Studies in urban areas have used wearable sensor technologies to measure concentration levels of particulate matter of multiple sizes (PM_{10}, $PM_{2.5}$, $PM_{0.1}$) (Boogaard et al., 2009; Correia et al., 2020; Good et al., 2016; Lin et al., 2020; Okokon et al., 2017; Peng et al., 2021; Qiu et al., 2019; Shrestha et al., 2020; Tran et al., 2021; Ueberham et al., 2019; Weichenthal et al., 2012; Wu et al., 2021; Jarjour et al., 2013), black carbon (Correia et al., 2020; Good et al., 2016; Lin et al., 2020; Okokon et al., 2017; Tran et al., 2021; Jarjour et al., 2013; MacNaughton et al., 2014), nitrogen dioxide (Shrestha et al., 2020; MacNaughton et al., 2014; Apparicio et al., 2016; Apparicio et al., 2021), carbon monoxide (Good et al., 2016; Shrestha et al., 2020; Jarjour et al., 2013), nitric oxide (Good et al., 2016; Shrestha et al., 2020), volatile organic compounds (VOCs) (Weichenthal et al., 2012; Wu et al., 2021), and sulfur dioxide (Shrestha et al., 2020). Half of these studies compared air pollution exposure while cycling to other travel modes (i.e., walking, e-scooter, motorcycle, car, bus, light rail) (Boogaard et al., 2009; Correia et al., 2020; Good et al., 2016; Lin et al., 2020; Okokon et al., 2017; Peng et al., 2021; Tran et al., 2021; Wu et al., 2021) while the remaining focused on cycling transport only (Qiu et al., 2019; Shrestha et al., 2020; Ueberham et al., 2019; Weichenthal et al., 2012; Jarjour et al., 2013; MacNaughton et al., 2014; Apparicio et al., 2016; Apparicio et al., 2021).

Alongside air pollution, researchers have assessed personal exposure of cyclists to noise (i.e., unwanted sound) using A-weighted sound pressure level (dB re 20 μPa, hereafter dBA) (Boogaard et al., 2009; Okokon et al., 2017; Ueberham et al., 2019; Apparicio et al., 2016; Apparicio et al., 2021). While there is evidence that road traffic noise may have a negative impact on mental health and cancer (Clark et al., 2020), certain sounds—particularly those from the natural world including birds singing and brooks babbling–may elicit health and well-being benefits. A meta-analysis showed that natural sounds were associated with decreased stress and annoyance and improved health and positive affective outcomes (e.g., decreased pain, improved mood) (Buxton et al., 2021). Previous personal exposure studies have not categorized sounds as anthropogenic or natural.

Research has shown extreme heat to be associated with lower urban trail use by cyclists (Lanza et al., 2022a) and to negatively impact cycling performance (Valenzuela et al., 2022). Heat exposure of cyclists warrants further investigation because cyclists have a high likelihood of exertional heat illness relative to other activities (Gamage et al., 2020). Air temperature and relative humidity—two environmental conditions that factor into heat stress (Kamath et al., 2023)—have been measured in a number of personal exposure studies (Good et al., 2016; Qiu et al., 2019; Shrestha et al., 2020; Wu et al., 2021; Apparicio et al., 2016; Apparicio et al., 2021). These studies included air temperature and relative humidity for correcting air pollution data, as descriptive data to complement air pollution modeling, and to explain variations in air pollution. Another study measured individual exposure to air temperature for the purpose of comparing with subjective measurements of cyclists. However, these prior studies did not measure air temperature, relative humidity, or heat index (i.e., heat stress metric comprising air temperature and relative humidity (Lanza et al., 2020)) as potential environmental hazards between and within different types of cycling routes.

Cycling outdoors entails exposure to sunlight, which carries both positive and negative health implications. Sunlight exposure helps boost vitamin D production and is positively associated with mental health (Wang et al., 2023), yet overexposure to ultraviolet (UV) radiation has been linked to skin cancer, premature aging, cataracts, and immune system suppression (U.S. Environmental Protection Agency, 2023). Two studies using wearable dosimeters revealed that cyclists' personal exposure to UV radiation exceeded levels recommended by occupational and recreational guidelines (Kimlin et al., 2006; Serrano et al., 2010). Neither study assessed light intensity along cycling routes, which has implications for exposure to UV radiation as well as heat stress.

A subset of studies on ambient environmental exposures while cycling has assessed spatiotemporal differences in exposures. Most focused on air pollution (Correia et al., 2020; Good et al., 2016; Lin et al., 2020; Qiu et al., 2019; Shrestha et al., 2020; Weichenthal et al., 2012; Wu et al., 2021; Jarjour et al., 2013; MacNaughton et al., 2014; Apparicio et al., 2016; Apparicio et al., 2021) with a couple studies also measuring noise (Apparicio et al., 2016; Apparicio et al., 2021). Spatial factors linked to air pollution and noise exposure of cyclists include vehicular traffic intensity, road type, distance from road, and presence of vegetation (Correia et al., 2020; Good et al., 2016; Shrestha et al., 2020; Weichenthal et al., 2012; Wu et al., 2021; Jarjour et al., 2013; MacNaughton et al., 2014; Apparicio et al., 2016; Apparicio et al., 2021). Studies have also identified diurnal peaks in air pollution and noise, as well as seasonal differences (Lin et al., 2020; Qiu et al., 2019; Apparicio et al., 2021). There has not been an assessment of spatiotemporal differences in personal exposure of cyclists to anthropogenic sounds, natural sounds, heat, and light; or evaluation of environmental exposures on weekdays versus weekend days.

The objective of this study was to determine the personal exposure of cyclists to air pollution, sounds, heat, and light on a vegetated trail versus the road in an urban setting. We compared levels of ambient environmental exposures within and between these two types of cycling routes during different times of day and days of week. This study includes four new research contributions. First, we estimated exposures to anthropogenic and natural sounds, heat, and light while cycling. Second, we used the air pollution, sound, heat, and light data to develop a composite index of unhealthy exposures while cycling during the warm season. Third, we mapped environmental exposures on cycling routes on weekdays and weekend days. Lastly, we divided audio into natural and anthropogenic sounds using pretrained neural networks for source separation. Data from this study can serve as evidence to inform interventions for the promotion of healthy and safe urban cycling.

2. Materials and methods

2.1. Study setting

This study took place during September 2021 in the City of Austin, the capital of Texas in the Southwest U.S. and the tenth most populous U.S. city with approximately 1161 residents per square kilometer (Fig. 1) (U.S. Census Bureau, 2024). Located in a humid subtropical climate, Austin in September averages 26.2 °C (minimum temperature: 19.6 °C; maximum temperature: 32.7 °C) and 77 mm of precipitation (U.S. National Oceanic and Atmospheric Administration, 2024). We focused on two cycling routes in the center of downtown Austin with notable differences. The first study site—herein called the Trail Route—was a continuous, 16.0km-long loop trail that circles a 190-hectare lake in downtown Austin (Texas Parks and Wildlife Department, 2020). Publicly available year-round with about five million unique visits by cyclists, walkers, and runners annually (The Trail Conservancy, 2024a), the trail is surrounded by 473 ha of parkland consisting of a mix of woodland, mowed lawns, non-vegetated areas, and Grow Zones (i.e., areas no longer mowed that are able to return to woodland) (Siglo Group, 2015). The surface material of the 2–6 m-wide trail is primarily crushed granite excluding a 2 km-long boardwalk on the south shore and a few other places with concrete. Tree canopy covered approximately 44 % of the Trail Route within 25 m, in 2022 (City of Austin, 2022).

The second study site—herein called the Road Route—was a 17.1 km-long loop entirely on local neighborhood roads and city streets (MAF/TIGER Feature Class Code: S1400) without passage on highways or main arteries (U.S. Census Bureau, 2021). The route was recommended by a professional cyclist as a commonly traveled road route by local cyclists, and drawn in the mobile application Strava (Strava, Inc., San Francisco, California, USA). Along the entire Road Route, cyclists ride directly on or adjacent to the paved road, either sharing the road with cars, riding in a painted bicycle lane, or on a two-way cycle track within five meters of the roadway. The route takes cyclists through bustling portions of downtown and central Austin neighborhoods, with land use of adjacent parcels primarily single family (43 %) and commercial (17 %) (City of Austin, 2023). From data collected in 2020 by the Texas Department of Transportation, the mean annual average daily traffic along the Road Route was 5929 motor vehicles (standard deviation = 5907) in 2020, which is higher than the countywide mean of 4692 vehicles (standard deviation = 5193) (Texas Department of Transportation, 2023). Tree canopy covered approximately 23 % of the Road Route within 25 m, in 2022 (City of Austin, 2022).

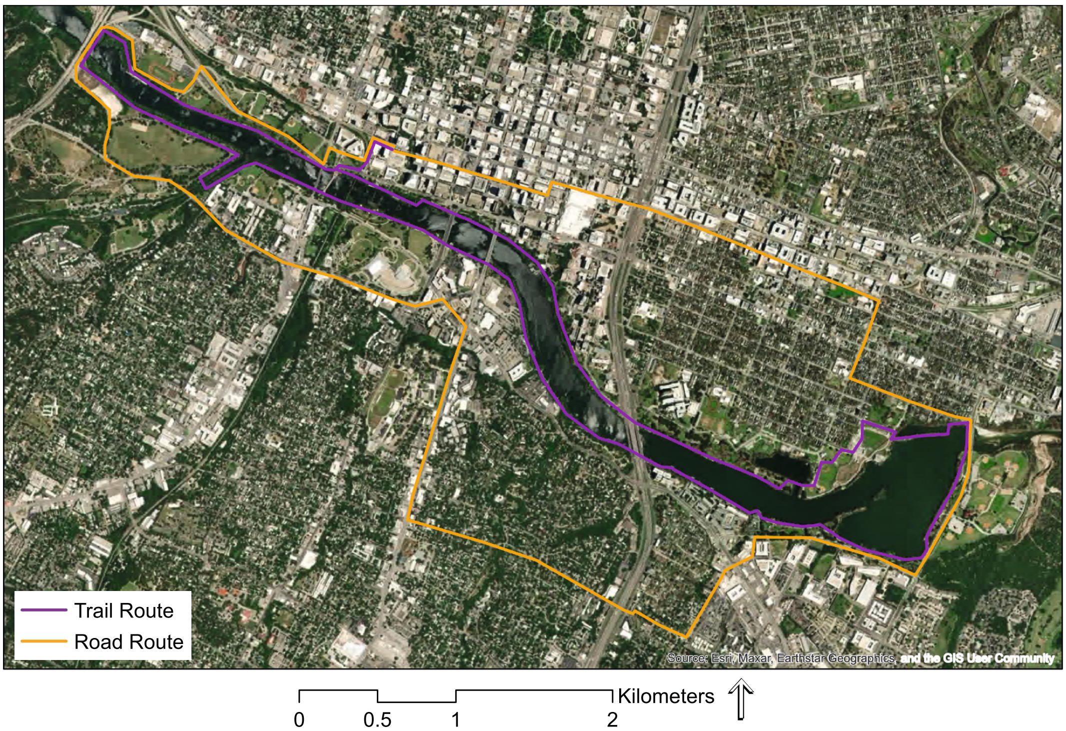

Fig. 1. Study sites of trail route and road route in Austin, Texas, USA.

2.2. Measurement of ambient environmental exposures

During the warm season on one weekday (Tuesday, September 7) and one weekend day (Sunday, September 12) in 2021, two cyclists—one on each route and outfitted with wearable and bicycle-mounted sensor technologies—rode the Trail Route and Road Route in the morning (7:30) and afternoon (17:30) ($n = 8$ total trips), times selected to represent peaks in U.S. non-motorized travel (U. S. Department of Transportation, 2020). Cyclists for both routes started at the same time and aimed to maintain a speed of about 16kmh, considered around the average speed of cycling to work in a previous study (Hendriksen et al., 2000). Cyclists were able to maintain this speed on both routes as the Trail Route included no traffic stops while the Road Route had a minimal number of traffic lights, one reason for the popularity of this route by local cyclists.

We measured personal exposure to $PM_{2.5}$ and total VOCs using a hip-worn Atmotube Pro sensor (Atmotech Inc., San Francisco, California, USA). Atmotube Pro utilizes light scattering technology to measure $PM_{2.5}$ every 1 s, and a metal-oxide sensor to measure total VOCs every 2 s. These data are then output to users as one-minute averages in μg/m^3 for $PM_{2.5}$ and parts per million for total VOCs. Readings from the Atmotube Pro for $PM_{2.5}$ have been shown to exhibit strong correlations ($0.79 < R^2 < 0.90$) with data from reference Federal Equivalent Method instruments in field tests (South Coast Air Quality Management District, 2024), and for total VOCs have been shown to be typically within 15 % of the measured value (Atmotech Inc, 2024).

Measurement of personal exposure to sounds relied on cyclists wearing F2 field recorders (Zoom Corporation, Chiyoda City, Tokyo, Japan). These light, compact, and battery-powered devices record continuously and include a high-precision internal clock, with audio files stored on a microSD card for later retrieval and processing (Zoom Corporation, 2024). Cyclists used the included belt clip to attach the recorder at their waist. To minimize wind obstruction and record sounds near ear level, the lavalier microphone with windscreen was clipped to the backside of cyclist at the shirt collar.

After calibrating field recorders (Supplementary Material), we applied a pretrained neural network to the audio file collected from the field recorders to extract anthropogenic and natural sounds from the base track. With the separated audio tracks, we estimated sound pressure levels (SPL) for each category of sound (Kong et al., 2023). This source-separation approach is distinct from classification, which does not allow for subsequent SPL measurement, and from traditional SPL measurements, which do not allow for the consideration of conceptual categories that may span multiple frequency bands. We trained the utilized network on the Google Audioset dataset, a collection of more than two million YouTube videos that are labeled according to an associated hierarchical ontology of 527 audio classes at the lowest level and seven at the highest level (i.e., Human Sounds; Source–Ambiguous Sounds; Animal; Sounds of Things; Music; Natural Sounds; and Channel, Environment and Background). Each of the low-level classes has at least 50 training samples (Google, 2024).

Sound inference by the trained model begins with a binary determination of the presence or absence of a requested class for each frame (0.01 s) of the recording. If the class is absent in a given frame, it is marked silent. If the class is present, it is extracted by the separation network. The average Signal-to-Distortion Ratio Improvement (SDRi)—a relative measure of the difference between signal-to-distortion ratios of a noisy signal with and without the application of source separation, whereby any positive value represents an improvement—across all classes was 6 dB. Well-represented classes in the training dataset tended to have above-average SDRi. Bird vocalizations, for example, have an SDRi of 15 dB, the 11th best of the 527 classes at the lowest level of the ontology.

For our analysis, we constructed a custom natural class by combining every subclass of the high-level Animal and Natural Sounds classes as defined by AudioSet. We excluded those events belonging to the Human Sounds class as these were irrelevant sounds from the human body. Our anthropogenic class was the combination of low-level AudioSet classes primarily under the Sounds of Things category. We excluded the subclass Wind Noise (Microphone) owing to possible correlation with bicycle velocity. We noted imperfect separation of classes in environments of high ambient sound. In our dataset, this consisted almost exclusively of vehicle sounds being included in our natural class. As the contamination was one way and involved low-frequency sounds, while the natural sounds (e.g., birdsong, insect noises) tended toward higher frequencies, we performed an additional 2000 Hz high-pass filter with a six dB roll-off per octave in Audacity® version 3.13 on sounds included in our natural class, thereby suppressing this category crossover at the cost of minimal information loss on low-frequency natural sounds.

We measured personal exposure to heat using MX2302A HOBO external air temperature/relative humidity sensor data loggers (Onset Computer Corporation, Bourne, Massachusetts, USA), per previous studies (Lanza et al., 2022b; Lanza et al., 2021; Larsen et al., 2023; Mallen et al., 2020). We relied on the same company for measuring personal exposure to light, using MX2202 HOBO pendant MX temperature/light data loggers. We used cable ties to mount both the data logger of the air temperature/relative humidity sensor and the light-measuring pendant to the bicycle handlebars, ensuring the position of sensors did not impede comfort and safety of cyclists. We encased each air temperature/relative humidity sensor in an RS3-B solar radiation shield to safeguard against biased measurement from absorption of incoming solar radiation. We made sure to position the light-measuring pendant flat on the bicycle handlebars to not distort light intensity readings. We specified both the air temperature/relative humidity sensor and light-measuring pendant to collect data every 1 s. The sensors are accurate ±0.2 °C from 0 to 70 °C, ±2.5 % from 10 to 90 % relative humidity, and ±10 % lux typical for direct sunlight (Onset Computer Corporation, 2024b; Onset Computer Corporation, 2024). In addition to measuring air temperature and relative humidity separately, we calculated heat index by following regression equations and corrections from Rothfusz and Steadman (U.S. National Weather Service, 2022).

To reveal how the combination of ambient environmental exposures at any given time could be unhealthy during the warm season, we developed a Negative Exposure Index, an equally weighted composite index (Goel et al., 2022; U.S. Centers for Disease Control and Prevention, 2023; Cepeda et al., 2017) comprising six exposures ($PM_{2.5}$, total VOCs, anthropogenic sounds, inverse of natural sounds, heat index, light intensity) where we calculated the average tertile after classifying values for each exposure into tertiles across the full dataset. Lastly, each cyclist wore a BT-Q1000XT GPS travel recorder (Qstarz International Co. Ltd., Taipei, Taiwan) to identify their geographic location over time, per earlier work (Lanza et al., 2022b; Lanza et al., 2021). We set GPS devices to log latitude and longitude every 1 s. To understand personal exposure levels across space and time, we time matched one-minute averages of all data collected from sensors.

2.3. Statistical analyses

To assess the relations between route type and ambient environmental exposures, we first calculated summary statistics (mean, standard deviation) of environmental exposures by route type, day of week, and time of day. We then specified linear mixed effects modeling to test the association between route type (1 = Trail Route, 0 = Road Route) and continuous variables for each environmental exposure, with a separate model for each exposure ($PM_{2.5}$, total VOCs, anthropogenic sounds, natural sounds, air temperature, relative humidity, heat index, light intensity) and the Negative Exposure Index ($n = 9$ models). Before modeling, we applied natural log transformations to the variables for $PM_{2.5}$, anthropogenic sounds, natural sounds, and light intensity so outcomes would be normally distributed. We adjusted final models for day of week (1 = weekday, 0 = weekend day) and time of day (1 = afternoon, 0 = morning), and added a random effect for rider to account for the correlation of outcomes from the same rider. We conducted statistical analyses using SAS version 9.4 (Cary, North Carolina, USA).

In addition to summary statistics and regression modeling, we used ArcGIS version 10.8 (Redlands, California, USA) to produce maps of spatially continuous linear estimates of ambient environmental exposures ($n = 45$ total maps). We estimated values between one-minute samples using inverse distance weighting in GIS (Lanza et al., 2021), and presented data as choropleth maps for each trip per route using tertile classification—these maps permit the comparison of each exposure by day of week and time of day. Lastly, we created maps of an equally weighted composite index (1–3) for each ambient exposure and the Negative Exposure Index where we calculated tertiles for each pair of trips and then compiled the four trip pairs into a single dataset before estimating values using inverse distance weighting—these index maps permit the identification of exposure levels at specific locations, adjusting for day of week and time of day.

3. Results

On average, cyclists on the Trail Route were exposed to higher levels of $PM_{2.5}$ and total VOCs compared to those on the Road Route (Table 1). $PM_{2.5}$ concentrations on the Road Route were often lower than levels recorded during study hours by a nearby continuous ambient monitoring station (Austin Webberville Road AF171, latitude = 30.2632°, longitude = −97.7129°) maintained by Texas Commission on Environmental Quality: weekday morning = 22.0 $\mu g\ m^{-3}$, weekday afternoon = 16.0 $\mu g\ m^{-3}$, weekend morning = 5.0 $\mu g\ m^{-3}$, and weekend afternoon = 10.0 $\mu g\ m^{-3}$ (Texas Commission on Environmental Quality, 2024). Anthropogenic sounds on the Trail Route were lower than on the Road Route while natural sounds were higher on the Trail Route. With decibels being on a logarithmic scale, these differences in sound levels equate to the Trail Route having anthropogenic sounds about one-quarter as loud as the Road Route and natural sounds about twice as loud. The Trail Route had lower air temperature and higher relative, with heat index lower on the Trail Route compared to the Road Route. These measurements on the Trail Route were either the same or lower than data recorded by a nearby weather station of the National Weather Service at Austin Camp Mabry (latitude = 30.3208°, longitude = −97.7604°): weekday morning = 25.0 °C, 79 %, 25.3 °C; weekday afternoon = 33.9 °C, 34 %, 33.9 °C; weekend morning = 25.0 °C, 71 %, 25.2 °C; and weekend afternoon = 31.7 °C, 38 %, 31.5 °C (San Diego County, 2008). Light intensity was lower on the Trail Route than the Road Route. Negative Exposure Index was 0.1 lower on the Trail Route versus the Road Route.

When comparing average levels of exposures by day of week and time of day (Table 2), $PM_{2.5}$ was higher in the morning than in the afternoon on both the Trail and Road Routes, while total VOCs were lower in the morning than in the afternoon. Anthropogenic sounds were higher on the weekday than the weekend on both routes except for the weekend morning when the Road Route averaged 87 dB, the highest level of data collection. Natural sounds were higher in the morning than afternoon on the Road Route, and on the weekends, natural sounds were higher during the morning than the afternoon. Regardless of day of week or time of day, air

Table 1
Summary statistics for ambient environmental exposures of cyclists on a Trail Route and Road Route in September 2021 in Austin, Texas, USA.

Model variable	Trail (n = 4)	Road (n = 4)
	Mean (SD)	Mean (SD)
$PM_{2.5}$ ($\mu g/m^3$)	10.5 (4.5)[a]	8.4 (3.3)
Total VOCs (ppm)	0.19 (0.07)[a]	0.06 (0.07)
Anthropogenic sounds (dB)	56 (25)	80 (8)
Natural sounds (dB)	52 (6)	44 (9)
Air temperature (°C)	27.7 (5.1)	28.8 (5.5)
Relative humidity (%)	65 (21)	60 (22)
Heat index (°C)	28.6 (5.8)	29.6 (6.0)
Light intensity (lx)	636 (564)	919 (838)
Negative Exposure Index (1–3)	1.9 (0.4)[a]	2.0 (0.4)

Sample sizes for one-minute averages of exposure data: Trail = 265, Road = 225.
[a] No $PM_{2.5}$ and total VOCs data on trail weekday morning because Atmotube Pro not turned on.

Table 2
Summary statistics for ambient environmental exposures of cyclists on a Trail Route and Road Route by day of week and time of day in September 2021 in Austin, Texas, USA.

Model variable	Trail morning (n = 2)	Road morning (n = 2)	Trail afternoon (n = 2)	Road afternoon (n = 2)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Weekday				
$PM_{2.5}$ (μg/m^3)	a	11.5 (4.1)	9.6 (2.2)	7.4 (0.7)
Total VOCs (ppm)	a	0.01 (0.01)	0.30 (0.02)	0.10 (0.02)
Anthropogenic sounds (dB)	56 (23)	76 (5)	63 (22)	81 (7)
Natural sounds (dB)	50 (6)	45 (8)	52 (6)	42 (9)
Air temperature (°C)	24.2 (0.7)	24.4 (0.6)	33.9 (0.7)	34.9 (0.4)
Relative humidity (%)	85 (2)	83 (2)	41 (3)	37 (1)
Heat index (°C)	24.6 (0.7)	24.8 (0.6)	35.4 (0.7)	36.1 (0.5)
Light intensity (lx)	460 (348)	549 (324)	1036 (806)	1658 (1178)
Negative Exposure Index (1–3)	1.6 (0.4)[a]	1.9 (0.3)	2.3 (0.2)	2.2 (0.2)
Weekend day				
$PM_{2.5}$ (μg/m^3)	11.0 (2.0)	8.9 (2.5)	11.0 (7.1)	5.8 (1.0)
Total VOCs (ppm)	0.10 (0.03)	0.01 (0.01)	0.20 (0.04)	0.20 (0.03)
Anthropogenic sounds (dB)	44 (30)	87 (8)	61 (19)	79 (6)
Natural sounds (dB)	54 (7)	50 (8)	53 (6)	40 (8)
Air temperature (°C)	21.6 (1.1)	21.7 (1.1)	31.7 (0.5)	33.0 (0.4)
Relative humidity (%)	85 (2)	82 (3)	48 (2)	42 (2)
Heat index (°C)	21.8 (1.1)	21.9 (1.1)	33.3 (0.5)	34.2 (0.5)
Light intensity (lx)	329 (244)	314 (126)	745 (421)	1058 (467)
Negative Exposure Index (1–3)	1.6 (0.2)	1.6 (0.2)	1.9 (0.2)	2.3 (0.2)

Sample sizes for one-minute averages of exposure data: Trail Morning = 136, Road Morning = 107, Trail Afternoon = 129, Road Afternoon = 118.
[a] No $PM_{2.5}$ and total VOCs data on trail weekday morning because Atmotube Pro not turned on.

temperature and heat index were always lower on the Trail Route compared to values recorded on concurrent bicycle rides on the Road Route, while relative humidity on the Trail Route was always higher than the Road Route. Light intensity was always lower in the morning than afternoon, with the Road Route on the weekday afternoon averaging 1658 lx, the highest level of data collection. The Negative Exposure Index was lower in the morning than the afternoon on weekdays and weekends for each route.

In fully adjusted regression models, we found that cycling on the Trail Route was associated with exposure to higher concentrations of $PM_{2.5}$ (b = 0.31; 95 % CI = 0.18, 0.44; p = 0.01) and total VOCs (b = 0.11; 95 % CI = 0.06, 0.17; p = 0.01) compared to the Road Route (Table 3). Cycling on the Trail Route was associated with lower exposure to anthropogenic sounds (b = −0.83; 95 % CI = −1.28, −0.38; p = 0.001) and higher exposure to natural sounds (b = 0.18; 95 % CI = 0.08, 0.50; p = 0.001) relative to the Road Route. Cycling on the Trail Route was associated with lower air temperature (b = −0.68; 95 % CI = −1.15, −0.22; p = 0.02) and higher relative humidity (b = 3.61; 95 % CI = 0.56, 6.66; p = 0.02) compared to the Road Route, with no statistically significant difference in heat index between routes (p = 0.06). Cycling on the Trail Route was associated with lower levels of light intensity (b = −0.36; 95 % CI = −0.47, −0.24; p = 0.01) than the Road Route.

Maps revealed differences in ambient environmental exposures depending on time of day and day of week as well as between and within route types (Figs. A.1–16). Natural sounds, for instance, were generally higher on the Trail Route than the Road Route (Fig. 2), yet in the morning, portions of the southernmost east-west segment of the Road Route had higher levels of natural sounds compared to the afternoon on both weekdays and weekend days. In the map illustrating the Negative Exposure Index across the eight total trips (Fig. 3), there are noticeable locations where the combination of $PM_{2.5}$, total VOCs, anthropogenic sounds, inverse of natural sounds, heat index, and light intensity is lower or higher than other locations such as a southwest segment of the Trail Route (purple star) and a northern segment of the Road Route (orange star), respectively.

Table 3
Output of adjusted regression models (n = 9) testing the relation between route type (Trail Route, Road Route) and ambient environmental exposures of cyclists in Austin, Texas, USA.

Model outcome	b	(95 % CI)	p
$PM_{2.5}$ (μg/m^3)	0.31	(0.13, 0.48)	0.001
Total VOCs (ppm)	0.11	(0.04, 0.19)	0.004
Anthropogenic sounds (dB)	−0.83	(−1.28, −0.38)	0.001
Natural sounds (dB)	0.18	(0.08, 0.50)	0.001
Air temperature (°C)	−0.68	(−1.26, −0.10)	0.022
Relative humidity (%)	3.61	(−0.20, 7.42)	0.064
Heat index (°C)	−0.49	(−0.99, 0.02)	0.061
Light intensity (lx)	−0.36	(−0.48, −0.23)	0.001
Negative Exposure Index (1–3)	−0.08	(−0.17, 0.01)	0.10

Independent variable of interest: route type (1 = Trail Route, 0 = Road Route). All models adjusted for day of week (1 = weekday, 0 = weekend day) and time of day (1 = afternoon, 0 = morning), and added a random effect for rider. All model outcomes were continuous.

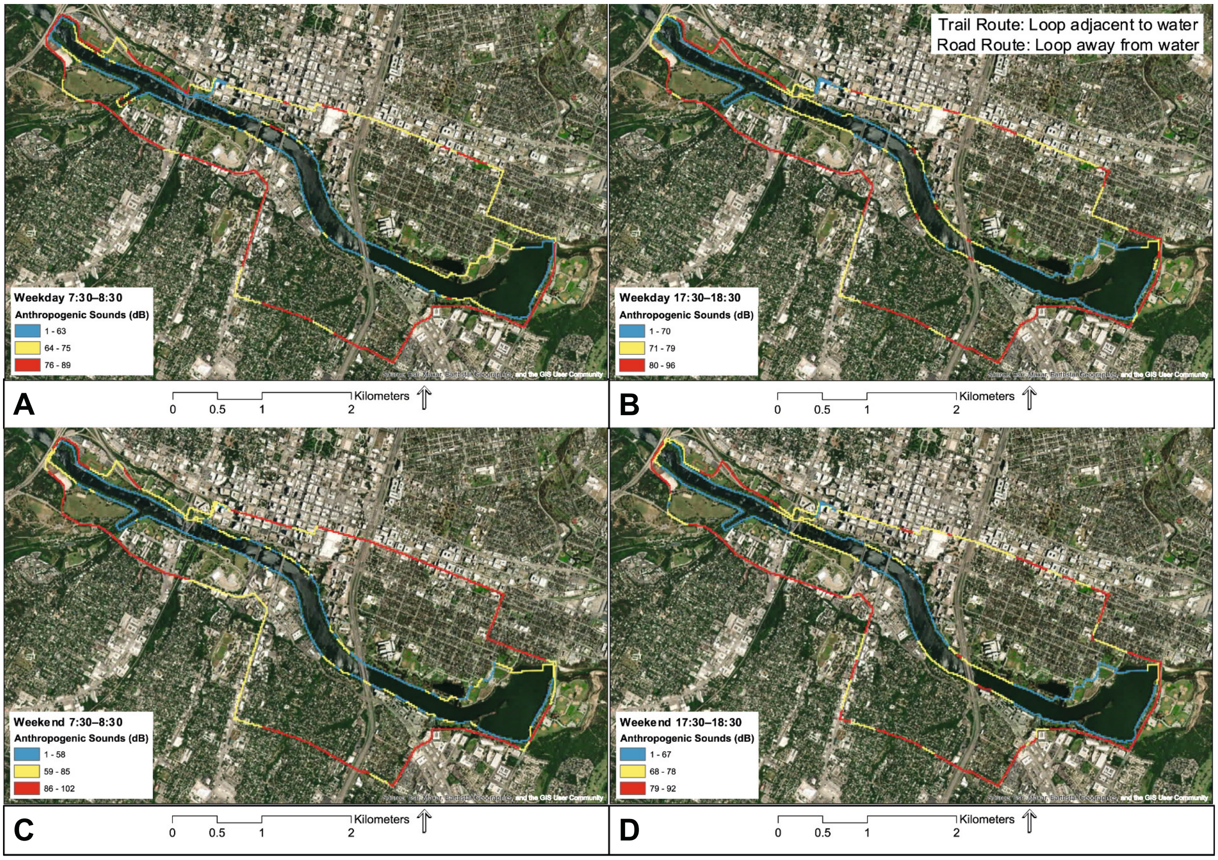

Fig. 2. Cyclists' exposure to natural sounds on Trail and Road Routes in Austin, Texas, USA, on A) weekday morning (7:30–8:30), B) weekday afternoon (17:30–18:30), C) weekend morning (7:30–8:30), and 2) weekend afternoon (17:30–18:30) in September 2021.

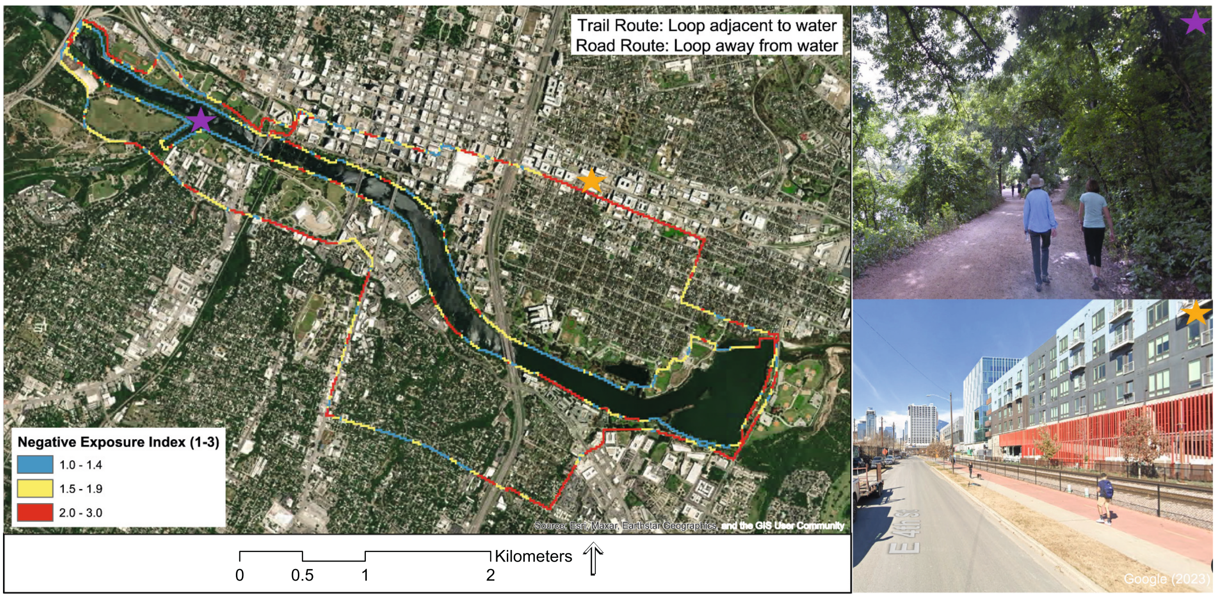

Fig. 3. Negative Exposure Index ($PM_{2.5}$, total VOCs, anthropogenic sounds, inverse of natural sounds, heat index, light intensity) on Trail and Road Routes in Austin, Texas, USA, across eight trips in the morning (7:30–8:30) and afternoon (17:30–18:30) on a weekday and weekend day in September 2021. Purple and orange stars on the map signify example locations on the Trail Route (top-right photo) and Road Route (bottom-right photo), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

We found significant differences in air pollution, sounds, air temperature, and light intensity while cycling on a vegetated, gravel trail compared to a nearby road route, with mapping showing differences in these environmental exposures within and between routes and by time of day and day of week. PM2.5 levels in our study were substantially lower than in studies conducted in Europe (Correia et al., 2020; Okokon et al., 2017) and Asia (Lin et al., 2020; Peng et al., 2021; Qiu et al., 2019; Wu et al., 2021) while comparable to those in the U.S. (Jarjour et al., 2013) and Australia (Shrestha et al., 2020). For instance, the average exposure of cyclists to $PM_{2.5}$ in Beijing, China, was 33.8 μg m^{-3} over a 24-h monitoring period (Lin et al., 2020), and in Berkeley, California, was 5.1 μg m^{-3} on a high-traffic commuting route (Jarjour et al., 2013). Compared to national ambient air quality standards, average $PM_{2.5}$ levels from wearable sensors were below the primary and secondary 24-hour $PM_{2.5}$ standards and the secondary one-year $PM_{2.5}$ standard across route types, days of week, and times of day; however, measured $PM_{2.5}$ concentrations exceeded the primary one-year $PM_{2.5}$ standard of 9.0 μg m^{-3} during the weekday morning on the Road Route, weekday afternoon on the Trail Route, and both weekend morning and afternoon on the Trail Route (Table 2) (U.S. Environmental Protection Agency, 2024). Our result that $PM_{2.5}$ levels on the Road Route were higher in the morning than afternoon supports previous findings on the exposure of cyclists to $PM_{2.5}$ and nitrogen dioxide (Qiu et al., 2019; Apparicio et al., 2021).

Our finding that the Trail Route was associated with significantly higher levels of $PM_{2.5}$ and total VOCs compared to the Road Route may be attributed to higher emissions of these particles and gases from biogenic sources on the Trail Route. The heavily vegetated Trail Route located primarily along the water's edge could mean relatively high concentrations of biological materials (e.g., pollen, mold spores) as particulates and VOCs (e.g., terpenoids, oxygenated VOCs) released from trees, shrubs, and grasses (Vivaldo et al., 2017). The crushed-granite surface material of the Trail Route could also be a source of fine soil and dust particles, the likes of which could be stirred up and suspended in the air from the foot traffic of approximately 14,000 pedestrians and cyclists using the trail each day (The Trail Conservancy, 2024a). Furthermore, we chose the Road Route because it had been identified as a preferred route by local cyclists, which may be in part because they perceived lower air pollution levels on this route of local roads than other options. The relatively low $PM_{2.5}$ and total VOCs levels on the Road Route corroborates previous literature that revealed lower levels of air pollution on residential streets and "alternative" routes (Good et al., 2016; Weichenthal et al., 2012; Wu et al., 2021; Jarjour et al., 2013; Apparicio et al., 2016).

The average levels of anthropogenic sounds on the Trail Route (56 dB) and Road Route (80 dB) can be categorized into the noise environments of quiet urban daytime and the higher limit of urban ambient sound, respectively, with 56dBA equivalent to light traffic at 30 m away and 80dBA equivalent to a garbage disposal at 1 m away (San Diego County, 2008). Anthropogenic sound levels on the Road Route were higher than the sound level considered generally safe for our hearing (70dBA) (U.S. National Institutes of Health, 2020), were higher than the average overall levels of noise (63–75dBA) experienced by cyclists in cities in Europe (Okokon et al., 2017; Ueberham et al., 2019) and Canada (Apparicio et al., 2016), and matched the noise levels recorded during cycling trips in Delhi, India (Apparicio et al., 2021). In the U.S., the Occupational Safety and Health Administration requires employers to implement programs to conserve hearing when noise exposure is at or above 85dBA averaged over eight working hours (U.S. Occupational Safety and Health Administration, 2024). About one-quarter (24 %) of the anthropogenic sound measurements on the Road Route reached this exposure limit, compared to less than 1 % (0.4 %) of measurements on the Trail Route (Fig. A.5).

The relatively high levels of anthropogenic sounds and the Road Route exhibiting a significant positive association with anthropogenic sounds compared to the Trail Route could be attributed to cyclists either directly riding alongside cars or on infrastructure immediately adjacent to them, and the relatively high traffic count on the route. For instance, studies in New Delhi, India, and Montreal, Canada, found cyclists to be exposed to higher levels of noise when traveling closer to vehicular traffic and on primary roads versus residential streets (Apparicio et al., 2016; Apparicio et al., 2021). Other anthropogenic sounds on the Road Route could be related to the route traveling through downtown, an area of Austin estimated to have received about 195,000 visitors; 65,000 workers; 35,000 residents daily in September 2021 (Austin Downtown Alliance, 2022), and construction noise from the historic amount of construction: in 2021, City of Austin added approximately 2.6 million square meters in residential development alone, its third most in a given year (City of Austin, 2024). Conversely, the Trail Route was at a distance from vehicular traffic and construction work, and buffered by vegetation.

In the morning and afternoon during both the week and weekend, natural sounds were higher on the Trail Route than Road Route. The Trail Route exhibiting a significant positive association with natural sounds compared to the Road Route could be due to the difference between the two settings as refuges for wildlife. The natural areas around the Trail Route—home to 850 animal species, 230 plant species, and 150 tree species (The Trail Conservancy, 2024b)—provide critical resources for wildlife including food, water, and shelter. In the area surrounding the Trail Route, songs from 89 bird species have been identified during fall migration (August–November) from 2019 to 2023 (eBird, 2024). This is in stark contrast to the environment of the Road Route, which traverses mostly built-up areas of downtown and its surrounding neighborhoods wherein residential and commercial parcels and right of ways have relatively low levels of vegetation and other natural features.

Light intensity was generally lower on the Trail Route than Road Route, where the higher intensity levels on weekday measurements compared to weekend day measurements could be related to clear sky conditions in the morning and afternoon on the weekday and the sky having few clouds in the morning and scattered clouds in the afternoon on the weekend day (U.S. National Centers for Environmental Information, 2024). These data, along with our finding that the Trail Route exhibited a significant negative association with both air temperature and light intensity relative to the Road Route, may signify that trees along the trail mitigate heat stress (via evapotranspiration and shading). In addition to vegetation, the lake the trail surrounds could also be cooling the air, as research has shown water bodies can lower air temperatures by as much as 0.6 °C via evaporation (Jacobs et al., 2020). Vegetation and water bodies are known to increase relative humidity levels but not at the expense of overall heat stress reduction (Li et al., 2024; Hong et al., 2023). For instance, previous research has shown trees to lower wet bulb globe temperature—a heat stress measure that estimates the combined effect of air temperature, relative humidity, wind speed, and radiation—by 3.3 °C, on average (Lanza et al., 2025).

With climate change increasing levels of temperature and air pollutants (USGCRP, 2023), coupled with our psychological disconnect from the natural world (Louv, 2011), there is opportunity to develop a cycling network that exposes riders to the sounds and aesthetics of nature where trees mitigate heat stress, filter pollutants, and buffer anthropogenic sounds, all the while ensuring that the natural and human-made sources of air pollutants are below harmful levels. Results reveal that urban cycling policies should be developed with spatiotemporal heterogeneity of environmental exposures in mind. Findings can serve as evidence for designing built environment interventions that physically separate cyclists from the pollution and noises of vehicular traffic while routing them through environments with trees, natural water bodies, and other features supportive of wildlife in urban areas.

Along with results from statistical analysis, this study provides a low-cost data collection protocol—consisting of cyclists equipped with four environmental exposure sensors and one GPS device simultaneously collecting data at predefined routes and times—can be utilized by municipalities to reveal exposure hot spots of multiple concurrent exposures in both existing and planned infrastructure investments in active transportation networks. The Negative Exposure Index is an indicator than can assist with identifying those priority areas for mitigation of unhealthy exposures and with facilitating the selection of interventions that attend to several types of exposures. Allocation of resources to reduce hazardous exposures should be based on the environmental and social context of the location of interest. For instance, municipalities in warm climates may prioritize heat management while those at high altitudes with elevated risk of UV exposure may rank minimizing light intensity above other environmental exposures. Tree planting can be prioritized in communities with higher proportions of Black, Latino, and low-income households, as these communities have been shown to have lower levels of tree canopy coverage (Lanza et al., 2019).

Of particular note is our use of a pretrained neural network to separate sounds in audio files into sound classes, which is a flexible process that permits the user to focus on the sound classes of interest in any setting. We showcased how to parse soundscapes into conceptual categories rather than by objective acoustic measures. Such categories may be broad—as in our case—or fine-grained, suggesting potential applicability to an array of research questions. Nevertheless, the present capabilities of universal source separation networks prevent them from being as broadly applicable as they might otherwise be. In our study, they were effective at extracting broadband anthropogenic sound without further processing. However, the crossover of limited background vehicle sound into natural sound tracks necessitated a frequency-based filter for the results to be usable for SPL estimation. This proved to be appropriate for our dataset, as the natural sounds tended to be higher frequency while the contaminating vehicle sounds tended to be lower frequency. Yet it belies one of the strengths of the approach, which is to disentangle categories of sound sources even where well-established objective measures such as intensity or frequency filters would leave them entangled. We relied on those filters in this study, ultimately using a combination of approaches that are not applicable to all datasets.

This study has limitations that can be addressed in future work. First, we did not collect data on $PM_{2.5}$ and total VOCs on the Trail Route during the weekday morning because the Atmotube Pro was not turned on correctly, decreasing our sample size and inhibiting the comparison of concentrations of these air pollutants to those measured at other times and on the Road Route. Second, sensor response time (i.e., amount of time it takes for a sensor to detect and react to a change in the measured quantity) could limit the validity of our assessment of personal exposure levels across space and time. Onset Computer Corporation listed the MX2302A HOBO to have response times of 6.5 min and 0.5 min for its temperature and relative humidity sensors, respectively (Onset Computer Corporation, 2024b), and the MX2202 HOBO to have a spectral response that matches the photopic response of the human eye (Onset Computer Corporation, 2025). No other sensors used in this study have published response times. Any response time of a sensor that is higher than the one-minute average that we used in our analysis to assess personal exposure levels would have higher potential for inaccurate measurements. Future technological improvements in low-cost sensors should support exposure assessments with appropriate response times for the given research question. Third, time-matching environmental exposure data with geographic location data enabled us to identify exposure hot spots along cycling routes but does not provide other spatial context such as the potential source of an exposure. For instance, we did not foresee that Sunday morning would be the time when anthropogenic sound levels would be highest, on average, on the Road Route—this could have been related to street sweeping or other types of noisy events either typical of that time or as outliers. Increasing the number of study days across different times of day and days of week, as well as complementing our data collection with traffic and construction schedules, could help us better understand our findings. Lastly, the Negative Exposure Index had equal weighting when in reality, certain exposures could be more detrimental to health than others. The composite index was also developed where the direction of each exposure would be considered negative during the warm season in a humid subtropical climate when in other locales and/or seasons, the direction of exposures may change. For example, in the winter, low temperatures would be considered negative while light intensity may be considered positive.

5. Conclusions

This study was an assessment of personal environmental exposures while cycling on a gravel hike-and-bike trail compared to a route on or along the road in Austin, Texas, during the warm season. Compared to the Road Route, the Trail Route was associated with significantly higher levels of $PM_{2.5}$, total VOCs, and natural sounds and with lower levels of anthropogenic sounds, air temperature, and light intensity, with mapping illustrating differences within and between routes at different times. While findings do not provide definitive evidence for one route type over another with respect to all environmental exposures, results support future investments in nature-based solutions along cycling routes to minimize environmental exposure harms and maximize benefits. Tree planting is an investment that—along with serving as a climate adaptation strategy—mitigates climate change by sequestering carbon and potentially encouraging modal shift from personal vehicle to bicycle. With lower temperatures and an improved soundscape on the Trail Route versus the Road Route, municipalities should consider illustrating these benefits to the public (e.g., educational signage), and providing equitable physical and cultural access to these vegetated routes.

CRediT authorship contribution statement

Kevin Lanza: Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Brendan Allison:** Writing – original draft, Visualization, Formal analysis, Data curation. **Baojiang Chen:** Writing – review & editing, Formal analysis. **Preston S. Wilson:** Writing – original draft, Formal analysis. **Ethan T. Hunt:** Writing – review & editing, Investigation. **Kathryn G. Burford:** Writing – review & editing, Investigation. **Yuzi Zhang:** Writing – review & editing, Investigation. **Leigh Ann Ganzar:** Writing – review & editing, Investigation. **Timothy H. Keitt:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2025.102429.

Data availability

Data presented in this study are available to access in the data repository Figshare: 10.6084/m9.figshare.26771599.

References

Apparicio, P., Carrier, M., Gelb, J., Séguin, A.-M., Kingham, S., 2016. Cyclists' exposure to air pollution and road traffic noise in central city neighbourhoods of Montreal. J. Transp. Geogr. 57, 63–69.
Apparicio, P., Gelb, J., Jarry, V., Lesage-Mann, É., 2021. Cycling in one of the most polluted cities in the world: exposure to noise and air pollution and potential adverse health impacts in Delhi. Int. J. Health Geogr. 20, 1–16.
Atmotech Inc, 2024. Atmotube Technical Specifications. https://atmotube.com/atmotube-support/atmotube-technical-specification.
Austin Downtown Alliance, 2022. State of downtown report 2021. https://downtownaustin.com/economic-development/state-of-downtown/state-of-downtown-report-2021/. Accessed 25 July 2024.
Boogaard, H., Borgman, F., Kamminga, J., Hoek, G., 2009. Exposure to ultrafine and fine particles and noise during cycling and driving in 11 Dutch cities. Atmos. Environ. 43, 4234–4242.
Buxton, R.T., Pearson, A.L., Allou, C., Fristrup, K., Wittemyer, G., 2021. A synthesis of health benefits of natural sounds and their distribution in national parks. Proc. Natl. Acad. Sci. 118, e2013097118.
Cepeda, M., Schoufour, J., Freak-Poli, R., Koolhaas, C.M., Dhana, K., Bramer, W.M., et al., 2017. Levels of ambient air pollution according to mode of transport: a systematic review. Lancet Public Health 2, e23–e34.
City of Austin, 2022. Tree canopy 2022. https://data.austintexas.gov/Locations-and-Maps/Tree-Canopy-2022/943x-7cq5/about_data. Accessed 21 January 2024.
City of Austin, 2023. Land use inventory detailed. https://data.austintexas.gov/dataset/Land-Use-Inventory-Detailed/7vsm-dvxg/about_data. Accessed 21 January 2024.
City of Austin, 2024. New residential development in Austin. https://data.austintexas.gov/stories/s/New-Residential-Development-in-Austin/wq6n-itt3/. Accessed 25 July 2024.
Clark, C., Crumpler, C., Notley, H., 2020. Evidence for environmental noise effects on health for the United Kingdom policy context: a systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer, dementia, birth, reproductive outcomes, and cognition. Int. J. Environ. Res. Public Health 17, 393.
Correia, C., Martins, V., Cunha-Lopes, I., Faria, T., Diapouli, E., Eleftheriadis, K., et al., 2020. Particle exposure and inhaled dose while commuting in Lisbon. Environ. Pollut. 257, 113547.
De Hartog, J.J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118, 1109–1116.
De Nazelle, A., Bode, O., Orjuela, J.P., 2017. Comparison of air pollution exposures in active vs. passive travel modes in European cities: a quantitative review. Environ. Int. 99, 151–160.
eBird, 2024. Bird observations: Town Lake Park (HOTE 042), Austin. https://ebird.org/barchart?byr=2019&eyr=2023&bmo=8&emo=11&r=L129110. Accessed 25 July 2024.
Gamage, P.J., Fortington, L.V., Finch, C.F., 2020. Epidemiology of exertional heat illnesses in organised sports: a systematic review. J. Sci. Med. Sport 23, 701–709.
Goel, R., Goodman, A., Aldred, R., Nakamura, R., Tatah, L., LMT, Garcia, et al., 2022. Cycling behaviour in 17 countries across 6 continents: levels of cycling, who cycles, for what purpose, and how far? Transp. Rev. 42, 58–81.
Good, N., Mölter, A., Ackerson, C., Bachand, A., Carpenter, T., Clark, M.L., et al., 2016. The Fort Collins Commuter Study: impact of route type and transport mode on personal exposure to multiple air pollutants. J. Expo. Sci. Environ. Epidemiol. 26, 397–404.
Google, L.L.C., 2024. AudioSet ontology. https://research.google.com/audioset/ontology/index.html.

Hendriksen, I.J., Zuiderveld, B., Kemper, H.C., Bezemer, P.D., 2000. Effect of commuter cycling on physical performance of male and female employees. Med. Sci. Sports Exerc. 32, 504.
Hong, C., Qu, Z., Xu, W., Gu, Z., 2023. Study on water cooling island effects under different climatic conditions. City and Built Environment. 1 (1), 4. Feb 6.
Jacobs, C., Klok, L., Bruse, M., Cortesão, J., Lenzholzer, S., Kluck, J., 2020. Are urban water bodies really cooling? Urban Clim. 32, 100607.
Jarjour, S., Jerrett, M., Westerdahl, D., de Nazelle, A., Hanning, C., Daly, L., et al., 2013. Cyclist route choice, traffic-related air pollution, and lung function: a scripted exposure study. Environ. Health 12, 1–12.
Kamath, H.G., Martilli, A., Singh, M., Brooks, T., Lanza, K., Bixler, R.P., Coudert, M., Yang, Z.L., Niyogi, D., 2023. Human heat health index (H3I) for holistic assessment of heat hazard and mitigation strategies beyond urban heat islands. Urban Clim. 52, 101675. Nov 1.
Kimlin, M.G., Martinez, N., Green, A.C., Whiteman, D.C., 2006. Anatomical distribution of solar ultraviolet exposures among cyclists. J. Photochem. Photobiol. B Biol. 85, 23–27.
Kong, Q., Chen, K., Liu, H., Du, X., Berg-Kirkpatrick, T., Dubnov, S., et al., 2023. Universal Source Separation With Weakly Labelled Data. arXiv preprint arXiv: 230507447.
Lanza, K., Stone Jr., B., Haardörfer, R., 2019. How race, ethnicity, and income moderate the relationship between urban vegetation and physical activity in the United States. Prev. Med. 121, 55–61. Apr 1.
Lanza, K., Stone, B., Chakalian, P.M., Gronlund, C.J., Hondula, D.M., Larsen, L., Mallen, E., Haardörfer, R., 2020. Physical activity in the summer heat: how hot weather moderates the relationship between built environment features and outdoor physical activity of adults. J. Phys. Act. Health 17 (3), 261–269. Mar 1.
Lanza, K., Alcazar, M., Hoelscher, D.M., Kohl, H.W., 2021 Dec. Effects of trees, gardens, and nature trails on heat index and child health: design and methods of the Green Schoolyards Project. BMC Public Health 21, 1–2.
Lanza, K., Gohlke, J., Wang, S., Sheffield, P.E., Wilhelmi, O., 2022a. Climate change and physical activity: ambient temperature and urban trail use in Texas. Int. J. Biometeorol. 66 (8), 1575–1588. Aug.
Lanza, K., Alcazar, M., Durand, C.P., Salvo, D., Villa, U., Kohl, H.W., 2022b. Heat-resilient schoolyards: relations between temperature, shade, and physical activity of children during recess. Journal of Physical Activity and Health. 20 (2), 134–141. Dec 23.
Lanza, K., Ernst, S., Watkins, K., Chen, B., 2025. Heat stress mitigation by trees and shelters at bus stops. Transp. Res. Part D: Transp. Environ. (140), 104653. Mar 1.
Larsen, L., Gronlund, C.J., Ketenci, K.C., Harlan, S.L., Hondula, D.M., Stone Jr., B., et al., 2023. Safe at home? A comparison of factors influencing indoor residential temperatures during warm weather among three cities. J. Am. Plann. Assoc. 89, 363–375.
Li, H., Zhao, Y., Wang, C., Ürge-Vorsatz, D., Carmeliet, J., Bardhan, R., 2024. Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait. Communications Earth & Environment. 5 (1), 1–4. Dec 10.
Lin, C., Hu, D., Jia, X., Chen, J., Deng, F., Guo, X., et al., 2020. The relationship between personal exposure and ambient PM2. 5 and black carbon in Beijing. Sci. Total Environ. 737, 139801.
Louv, R., 2011. The Nature Principle: Human Restoration and the End of Nature-Deficit Disorder. Algonquin Books.
MacNaughton, P., Melly, S., Vallarino, J., Adamkiewicz, G., Spengler, J.D., 2014. Impact of bicycle route type on exposure to traffic-related air pollution. Sci. Total Environ. 490, 37–43.
Mallen, E., Bakin, J., Stone, B., Sivakumar, R., Lanza, K., 2020. Thermal impacts of built and vegetated environments on local microclimates in an Urban University campus. Urban Clim. 32, 100640. Jun 1.
Okokon, E.O., Yli-Tuomi, T., Turunen, A.W., Taimisto, P., Pennanen, A., Vouitsis, I., et al., 2017. Particulates and noise exposure during bicycle, bus and car commuting: a study in three European cities. Environ. Res. 154, 181–189.
Onset Computer Corporation, 2024. MX2202 HOBO pendant MX temperature/light data logger. https://www.onsetcomp.com/products/data-loggers/mx2202. Accessed 21 January 2024.
Onset Computer Corporation, 2024b. MX2302A HOBO external temperature/rh sensor data logger. https://www.onsetcomp.com/products/data-loggers/mx2302a. Accessed 21 January 2024.
Onset Computer Corporation, 2025. HOBO® Pendant® MX Temp (MX2201) and Temp/Light (MX2202) Logger Manual. https://www.onsetcomp.com/sites/default/files/2023-05/21536-P%20MX2201%20and%20MX2202%20Manual.pdf. Accessed 13 March 2025.
Peng, L., Shen, Y., Gao, W., Zhou, J., Pan, L., Kan, H., et al., 2021. Personal exposure to PM2. 5 in five commuting modes under hazy and non-hazy conditions. Environ. Pollut. 289, 117823.
Pucher, J., Buehler, R., 2010. Walking and cycling for healthy cities. Built Environ. 36, 391–414.
Qiu, Z., Wang, W., Zheng, J., Lv, H., 2019. Exposure assessment of cyclists to UFP and PM on urban routes in Xi'an, China. Environmental Pollution 250, 241–250.
San Diego County, 2008. Table 1: sound levels of typical noise sources and noise environments. https://www.sandiegocounty.gov/dplu/docs/081024/TM5499-NOISE-T.pdf. Accessed 28 July 2024.
Serrano, M.A., Cañada, J., Moreno, J.C., 2010. Valencia RGoSRo Erythemal ultraviolet exposure of cyclists in Valencia, Spain. Photochemistry and photobiology 86, 716–721.
Shrestha, A., Mullins, B., Zhao, Y., Selvey, L.A., Rumchev, K., 2020. Exposure to air pollutants among cyclists: a comparison of different cycling routes in Perth, Western Australia. Air Qual. Atmos. Health 13, 1023–1034.
Siglo Group, 2015. The Butler Trail at Lady Bird Lake: Urban Forestry and Natural Area Management Guidelines. https://thetrailconservancy.org/wp-content/uploads/2023/05/Urban-Forestry-and-Natural-Area-Management-Guidelines_Butler-Trail_r.pdf.
South Coast Air Quality Management District, 2024. Air Quality Sensor Performance Evaluation Center Evaluation Summary: Atmotube Pro. http://www.aqmd.gov/docs/default-source/aq-spec/summary/atmotube-pro—summary-report.pdf?sfvrsn=8.
Tainio, M., Andersen, Z.J., Nieuwenhuijsen, M.J., Hu, L., De Nazelle, A., An, R., et al., 2021. Air pollution, physical activity and health: a mapping review of the evidence. Environ. Int. 147, 105954.
Texas Commission on Environmental Quality, 2024. Austin Webberville Road AF171 data by site by date (all parameters). https://www.tceq.texas.gov/cgi-bin/compliance/monops/daily_summary.pl?cams=171. Accessed 17 July 2024.
Texas Department of Transportation, 2023. TxDOT 5-year counts 2020. https://gis-txdot.opendata.arcgis.com/datasets/TXDOT::txdot-5-year-counts-2020/about. Accessed 21 January 2024.
Texas Parks & Wildlife Department, 2020. Lady Bird Reservoir 2019 fisheries management survey report. https://tpwd.texas.gov/publications/pwdpubs/media/lake_survey/pwd_rp_t3200_1385_2019.pdf. Accessed 21 January 2024.
The Trail Conservancy, 2024a. The Ann and Roy Butler Hike & Bike Trail. https://thetrailconservancy.org/discover/about-butler-trail/. Accessed 21 January 2024.
The Trail Conservancy, 2024b. Ecological restoration. https://thetrailconservancy.org/nature-conservation/. Accessed 25 July 2024.
Tran, P.T., Adam, M.G., Tham, K.W., Schiavon, S., Pantelic, J., Linden, P.F., et al., 2021. Assessment and mitigation of personal exposure to particulate air pollution in cities: an exploratory study. Sustain. Cities Soc. 72, 103052.
U.S. Census Bureau, 2021. 2021 TIGER/Line Shapefiles: Roads. https://www.census.gov/cgi-bin/geo/shapefiles/index.php?year=2021&layergroup=Roads. Accessed 21 January 2024.
U.S. Census Bureau, 2024. QuickFacts: Austin City, Texas. https://www.census.gov/quickfacts/fact/table/austincitytexas/LND110210.
U.S. Centers for Disease Control and Prevention, 2023. Health benefits of physical activity for children, adults, and adults 65 and older. https://www.cdc.gov/physicalactivity/basics/adults/health-benefits-of-physical-activity.html. Accessed 5 January 2024.
U.S. Department of Transportation, 2020. Federal Highway Administration 2017 National Household Travel Survey brief: non-motorized travel. https://nhts.ornl.gov/assets/FHWA_NHTS_Brief_Bike%20Ped%20Travel_041520.pdf. Accessed 21 January 2024.
U.S. Environmental Protection Agency, 2023. Health effects of UV radiation. https://www.epa.gov/sunsafety/health-effects-uv-radiation. Accessed 14 January 2024.
U.S. Environmental Protection Agency, 2024. National Ambient Air Quality Standards (NAAQS) for PM. https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm. Accessed 17 July 2024.

U.S. National Centers for Environmental Information, 2024. Local climatological data (LCD), version 2 (LCDv2). https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C01689/html. Accessed 17 July 2024.
U.S. National Institutes of Health, 2020. Do you know how loud is too loud? https://www.nidcd.nih.gov/news/2020/do-you-know-how-loud-too-loud. Accessed 28 July 2024.
U.S. National Oceanic and Atmospheric Administration, 2024. U.S. climate normals quick access. https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-monthly&timeframe=30&location=TX&station=USW00013904. Accessed 20 February 2024.
U.S. National Weather Service, 2022. The heat index equation. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml. Accessed 19 February 2024.
U.S. Occupational Safety and Health Administration, 2024. Occupational noise exposure. https://www.osha.gov/noise. Accessed 28 July 2024.
Ueberham, M., Schlink, U., Dijst, M., Weiland, U., 2019. Cyclists' multiple environmental urban exposures—comparing subjective and objective measurements. Sustainability 11, 1412.
USGCRP, 2023. In: Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C., Maycock, T.K. (Eds.), Fifth National Climate Assessment. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.
Valenzuela, P.L., Mateo-March, M., Zabala, M., Muriel, X., Lucia, A., Barranco-Gil, D., et al., 2022. Ambient temperature and field-based cycling performance: insights from male and female professional cyclists. Int. J. Sports Physiol. Perform. 17, 1025–1029.
Vivaldo, G., Masi, E., Taiti, C., Caldarelli, G., Mancuso, S., 2017. The network of plants volatile organic compounds. Sci. Rep. 7, 11050.
Wang, J., Wei, Z., Yao, N., Li, C., Sun, L., 2023. Association between sunlight exposure and mental health: evidence from a special population without sunlight in work. In: Risk Management and Healthcare Policy, pp. 1049–1057.
Weichenthal, S., Kulka, R., Bélisle, P., Joseph, L., Dubeau, A., Martin, C., et al., 2012. Personal exposure to specific volatile organic compounds and acute changes in lung function and heart rate variability among urban cyclists. Environ. Res. 118, 118–123.
Wu, T.-G., Chang, J.-C., Huang, S.-H., Lin, W.-Y., Chan, C.-C., Wu, C.-F., 2021. Exposures and health impact for bicycle and electric scooter commuters in Taipei. Transp. Res. Part D: Transp. Environ. 91, 102696.
Zoom Corporation, 2024. F2 field recorder & lavalier mic. https://zoomcorp.com/en/us/field-recorders/field-recorders/zoom-f2/#specs-panel. Accessed 22 January 2024.