Measuring and Mitigating Extreme-Heat Exposure in Urban Travel: Transferable, Data-Driven Methods for Walking and Transit

Extreme heat is an exogenous stressor on urban travel demand that the traveler does not control: it raises the physiological cost of a walk or a bus ride that still has to be made, while the shade over the sidewalk and the reach of the transit network are fixed on the timescale of a heat event. This dissertation contributes methods to measure that stressor at scale and the empirical laws they reveal, for the two travel modes with the least protection from heat and the fewest private alternatives: walking and public transit. The objects of study, the stressor, the adaptation infrastructure, and the exposure, are identified from observed data, and interventions are then simulated on those measured objects and validated out of sample where a prediction is involved.

The methodological contributions span the measurement pipeline and transfer across cities. To map the shade that reduces pedestrian heat exposure, the work introduces ShadowTransfer, a benchmark of 4,500 human-verified overhead shadow masks across three cities with a leave-one-city-out protocol, and the Spectral Information Bottleneck (SIB), a diagnosis-driven detector module. SIB is the only method evaluated with no catastrophic transfer failure across nine architecture-by-city cells, and it yields a per-edge sidewalk shade map produced by an identical procedure for every city. A shared data substrate extracts trips, heat, and built-environment layers from anonymized smartphone data, within-city Wet Bulb Globe Temperature panels, and transit schedules. For walking, route-level sun-exposure estimation places each trip on this shade map, and a budgeted, marginal-return optimizer sites awnings where trips already go. For transit, a coverage-controlled outdoor-heat-dose estimator measures the access, wait, and egress heat a rider absorbs, holding service coverage fixed so the dose is comparable across neighborhoods. A final method, Residual-Shape Reduction Search (RSR), reframes symbolic regression: the unit of search becomes one validated reduction of the residual rather than a whole candidate equation, so confirmed structure accumulates and the problem shrinks each round, reaching a result in tens of model calls against the baselines' registered one-thousand-call budget.

Applied at scale, the methods yield quantitative laws. Across 9.41 million walking trips in 34 U.S. cities, route choice reduces a trip's sun exposure by only 3.5%: a Phoenix hot-hour trip crosses about 1,283 sun-metres, and routing to its physical limit removes 45 of them, because the median sidewalk edge in every one of the 34 cities carries no measured shade and 67 to 99% of hot trips cannot reach a route meeting a 30% shade guideline. Because routing cannot reach shade that is absent, the awning optimizer adds it, but its effect on total exposure is bounded near 4%, and the relief lands where foot traffic is dense rather than

where heat exposure is greatest. For transit across 32 U.S. cities, a hot day suppresses standing demand by a 2024 median of 0.71% per °C, the marginal slope against the heat anomaly, steepening to a 1.22% per °C hot-versus-cool-day contrast during a heatwave (the 2022 Indiana and Ohio cities are reported apart at 1.72% per °C). This demand response does not vary with network structure across eight tests, so the network is a fixed stage and the intervention targets the outdoor heat riders accumulate rather than the demand they lose. The riders who continue to travel carry an outdoor heat dose 91.3 °C·min higher per morning-peak trip in directionally confined neighborhoods, positive in all 26 cities with a measurable coverage gap and unrelated to their residents' income or vehicle access, and a diagnosis-matched service change at a +5% peak-service budget reduces that dose in every computable city by a median 9,704 °C·min, 3.56% of the trips' base heat, concentrated on the confined riders who bore the most. On a decomposable target the monolithic methods do not solve, RSR outperforms a faithful reimplementation of the strongest published scheme out of sample at roughly a sixtieth of the compute; applied to heat-driven mobility, it recovers a law governing the timing of travel rather than its volume, in which above a city-specific temperature threshold car-less and low-income residents shift when they travel rather than how much, and the law transfers within the 2024 vintage to cities held out of the search.

Across both modes the finding is the same: heat exposure on the trips people still make is set by infrastructure the traveler cannot change, so behavioral adaptation alone cannot reduce it, and relief requires adding shade and service reach where travelers are most exposed. The walking, transit, and discovery analyses converge on one equity result, that the residents who must adapt on a real trip and cannot opt out of it are disproportionately the car-less and the low-income, reached in turn from route exposure, rider exposure, and an automatically discovered timing law. Each intervention is reported with its upper bound on effectiveness rather than its best case: added shade removes about 4% of pedestrian exposure and a budgeted service change about 3.6% of a rider's outdoor heat. Determining which intervention to place is largely established; deploying, funding, and coordinating those interventions is the remaining problem.