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SCHOOL OF SUSTAINABLE ENGINEERING AND THE BUILT ENVIRONMENT

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Quantifying Vehicle Waste Heat: A Case Study of Phoenix, Arizona

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Quantifying vehicle waste heat: A case study of Phoenix, Arizona

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1 INTRODUCTION

Mitigation of urban heat islands has become a goal for research and policy as urban environmental heat is a rapidly growing concern. Urban regions such as Phoenix, AZ are facing projected warming as urban populations grow and global climates warm (McCarthy et al. 2010), and severe urban heat can even lead to human mortality and morbidity (Berko et al. 2014). Increased urban heat may also have social and economic consequences such as by discouraging physical activity, reducing outdoor accessibility, and decreasing economic output (Stamatakis et al. 2013; Karner et al. 2015; Obradovich & Fowler 2017; Kjellstrom et al. 2009). Urban heat islands have been well documented in academic literature (Oke 1982; Arnfield 2003), and anthropogenic waste heat is often a major factor. The American Meteorological Society (2012) has said that anthropogenic waste heat may contribute "15 – 50 W/m^2 to the local heat balance, and several hundred W/m^2 in the center of large cities in cold climates and industrial areas."

Anthropogenic waste heat from urban vehicle travel may be a notable contributor to the urban heat balance and the urban heat island effect, but little research has quantified and explored how changes in vehicle travel may influence local climates. Even with recent rapid improvements to engine efficiencies, modern automobiles still convert small amounts of fuel to useful energy. Typically, around two-thirds of energy from fuel in internal combustion engine vehicles is lost as waste heat through exhaust and coolant (Hsiao et al. 2010; Yu & Chau 2009; Saidur et al. 2009; Endo et al. 2007), and as much as 80% of fuel energy can be lost to waste heat under poor conditions (Orr et al. 2016). In addition, combustion of fuel generates water vapor and air pollution which may also affect the urban climate. **Figure 1** displays where a typical combustion engine's fuel energy is used and lost. There has been little research that quantifies the influence of vehicle travel on urban anthropogenic waste heat. According to Sailor and Lu (2004), most cities have peak anthropogenic waste heat values between 30 and 60 W m^{-2} (averaged across city) and heating from vehicles could make up as much as 62% of the total in summer months. Additionally, they found that vehicle waste heat could account for up to 300 W m^{-2} during rush hours over freeways. In another study, Hart & Sailor (2009) used in situ measurements in Portland, OR to evaluate spatial variability of air temperatures on urban roadways. They found that air masses near major roadways are some of the warmest in the region. Although some of the warming is attributed to pavement characteristics (imperviousness, low albedo), an average increase of 1.3 C was observed on weekdays relative to weekends along roadways. The authors offer increased weekday traffic density and building use as the likely contributors to this discrepancy. These previous studies indicates that vehicle related waste heat could be an important consideration in the urban energy balance. If significant, there may exist viable strategies to reduce anthropogenic waste heat from urban vehicle travel by increasing the fleet fuel economy and shifting to electric vehicles. This could offer cooling in urban areas around roadways were pedestrians are often found. **Figure 2** visually demonstrates waste heat from vehicles (including an electric vehicle) in two thermal images.

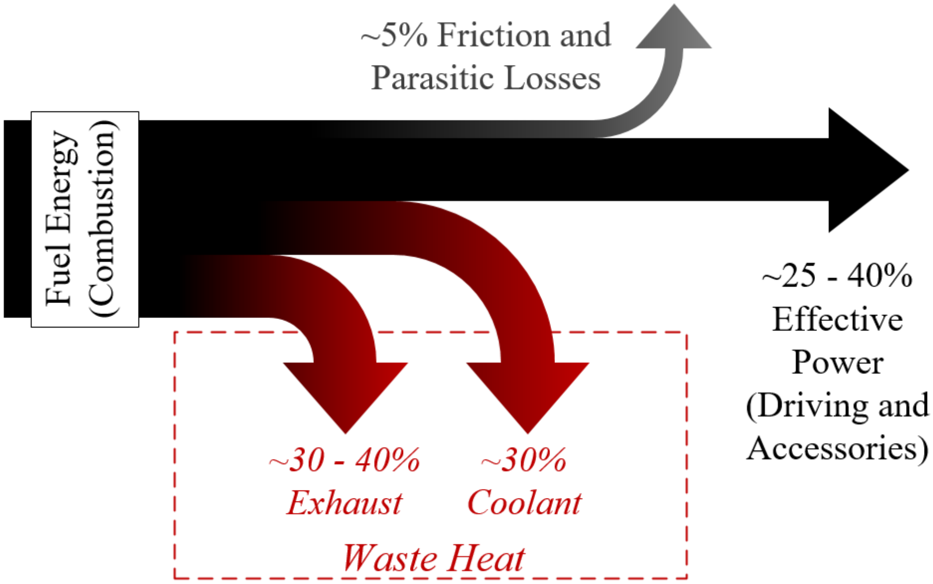

Figure 1 – Example of energy flow from fuel in a typical automotive combustion engine (adapted from Fu et al. 2011).

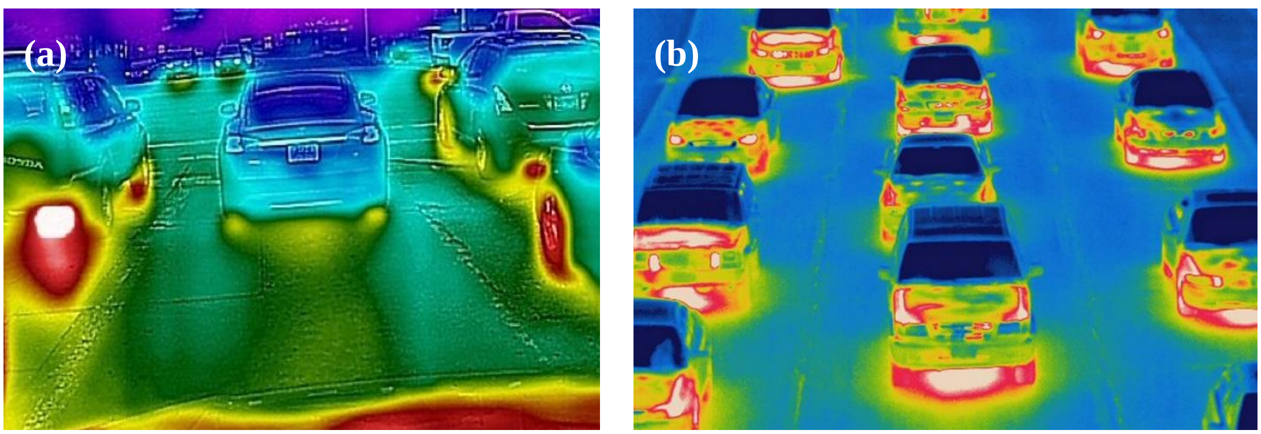

Figure 2 – Thermal images showing waste heat hotspots of (a) a Tesla electric vehicle (center) next to internal combustion engine vehicles, and (b) vehicles on a highway.
Sources: (a) http://www.texasengineer.com/Pages/WasteHeat.aspx; (b): http://tyronefoto.com/thermal-flight.

By answering two research questions specific to Maricopa County and the greater Phoenix metropolitan region, this research looks to improve the knowledge on vehicle travel's contribution to anthropogenic waste heat in urban regions:

1. What is the spatial and temporal impact of urban vehicle travel on urban anthropogenic waste heat in Maricopa County and the greater Phoenix metropolitan region?
2. To what extent could increases in vehicle efficiencies in the fleet penetration reduce anthropogenic waste heat in Maricopa County and the greater Phoenix metropolitan region?

2 METHODOLOGY

To estimate the spatial and temporal urban anthropogenic waste heat magnitude in the Phoenix metro, multiple data sources are referenced to estimate daily vehicle travel profiles, ratios of energy lost to waste heat in automotive engines, and fuel consumption by vehicle types. Waste heat estimates are examined under various spatial aggregation extents to better understand the importance of scale when estimating waste heat. Finally, various scenarios of improved vehicle fuel efficiencies are evaluated to identify potential for reducing the magnitude of anthropogenic waste heat in the urban transport sector.

2.1 DATA SOURCES

The 2009 National Household Travel Survey (NHTS) is used to estimate personal (light duty) vehicle daily travel times and yearly fuel consumption (USDOT & FHWA 2009). 2016 traffic volumes for light duty and heavy duty vehicles on Arizona Highways are also utilized via the Arizona Department of Transportation's (ADOT) Average Annual Daily Traffic (AADT) data (ADOT 2016). Transit vehicle fuel consumption is referenced from the National Transit Database (NTD 2016). Multiple studies are referenced to estimate realistic ranges of waste heat generated by vehicle travel (Hsiao et al. 2010; Reddy et al. 2015; Yu & Chau 2009; Ohashi et al. 2007; Endo et al. 2007).

2009 NHTS data is used to estimate light duty vehicle daily travel times and fuel consumption for the greater Phoenix metro by filtering to only households and trips in Maricopa County. Person and household weightings are used to estimate population level trip and fuel statistics. Replicate weights and replicate weighting methods are also used in accordance with the NHTS guidelines to obtain a margin of error in Maricopa population level estimates (USDOT & FHWA 2011). In Maricopa County, there were 8,468 different vehicles used across 4,201 households and respondents engaged in 31,654 total trips.

Highway traffic data is obtained from ADOT for all major highways in Maricopa County to include heavy duty (freight) waste heat and to allow estimates at the highway scale. AADT is traffic count data for light duty and heavy duty vehicles across marked sections of the highways where tools count vehicles that pass over time. All highway data for the 2015 calendar year is referenced. Fleet average fuel economies for light and heavy duty vehicles for 2016 are obtained from the Bureau of Transportation Statistics (USDOT & FHWA 2017).

Transit data is obtained from the National Transit Databases' inventory of fuel and energy use by transit agency. All fuel consumption data for transit agencies within Maricopa County for the year of 2016 are included. Electric energy is excluded because it is assumed that waste heat is not significant from electric transit vehicles (e.g. electrified rail). All other fuel types are included.

For spatial aggregation of waste heat, area estimates are made at four different spatial levels to evaluate how spatial aggregation may influence the magnitude of waste heat estimates. The four levels are: at the county level, at the incorporated county level (cities only), at the highway level (area directly enclosing highways), and at a neighborhood level. Data at the county and city level is obtained from the Arizona State University Geospatial Data Library[1]. Maricopa County is 9,224 mi^2 and incorporated Maricopa is 2,070 mi^2. Highway widths are not measured but assumed a constant width (see next section). The neighborhood level spatial

[1] https://lib.asu.edu/geo/data

aggregation is a case study of approximately 1.15 mi^2 region encasing the I-10 and I-17 interchange in south Phoenix. **Figure 3** shows three of the four spatial scales examined and

Figure *4* shows the fourth scale (neighborhood scale).

Once baseline estimates are made, various scenarios of increased fuel economies are tested. Using current estimates of higher performing MPG vehicles (including electric vehicles), the potential reduction in waste heat magnitudes is quantified. Because on-road MPG and EPA rated MPG estimates differ, on-road MPG estimates are adjusted based on the Maricopa travel patterns in the NHTS (e.g. 55/45 city/highway driving is not entirely accurate during actual driving patterns).

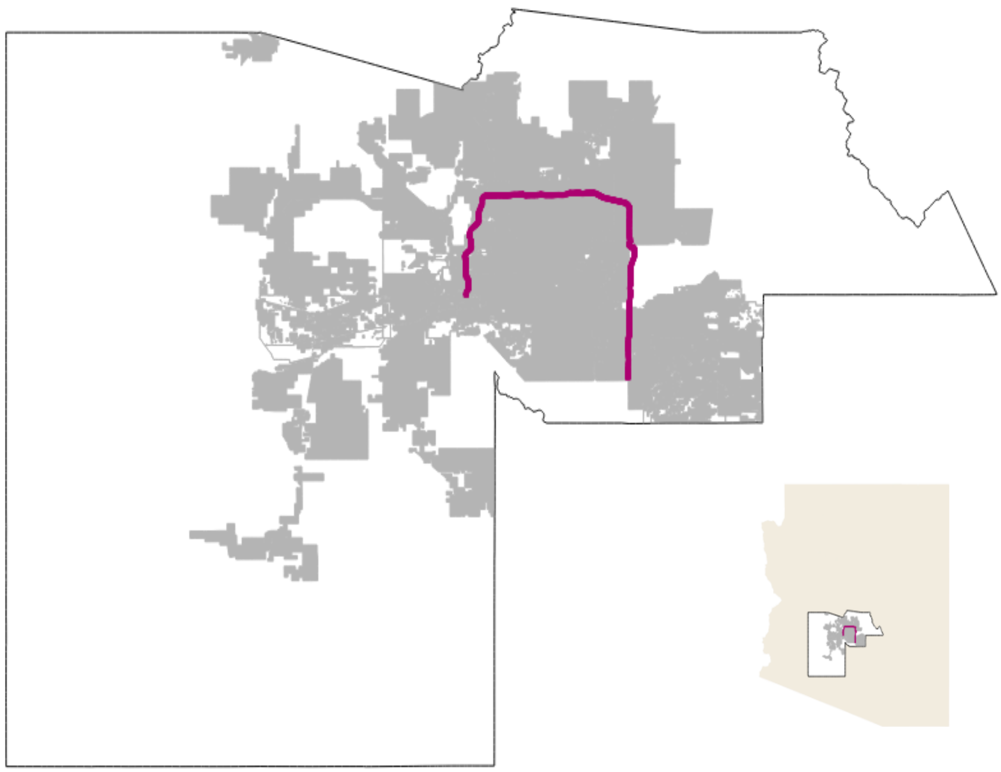

Figure 3 – Three of the four spatial scales studied: Maricopa County (border), Incorporated Maricopa County (gray area), and at the highway scale (purple, AZ 101 highway).
Note that the highway's thickness shown is not drawn to scale but is instead a larger thickness for visualization. The fourth scale, is visualized separately on a smaller scale (see following figure).

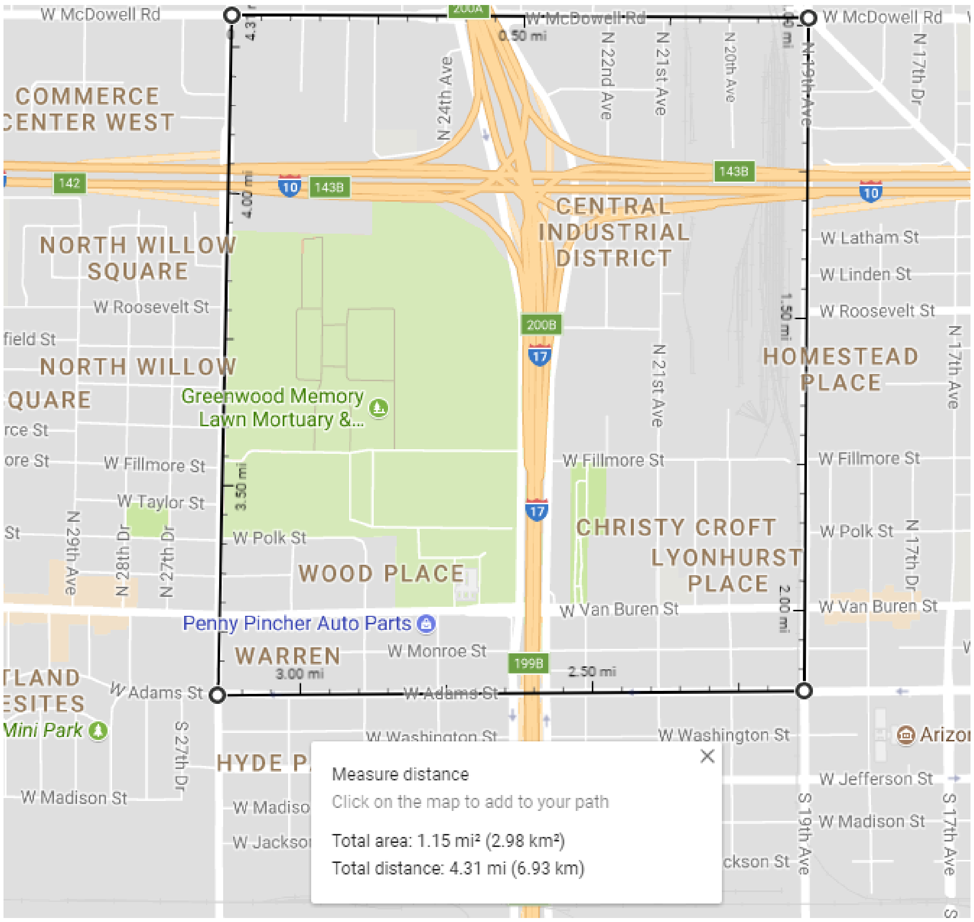

Figure 4 – Fourth spatial scale: neighborhood encasing the I-10 and I-17 interchange in south Phoenix.
Image source: Google Maps.

2.2 Equations for Estimating Waste Heat

Using the previously detailed data, vehicle waste heat across a given spatial extent over a given time is estimated using the following set of equations

$$\phi_{q,t,s} = Q_e * V_{f,t,s} * u_{gas} * t^{-1} * A_s{}^{-1} \tag{1}$$

$$V_{f,t,s} = VMT_{t,s} * MPG_{e,s,t}{}^{-1} \tag{2}$$

where $\phi_{q,t,s}$ is waste heat (heat flux, in $\mathrm{W \cdot m^{-2}}$) from vehicle travel within space s during time t, Q_e is the average percent fuel energy lost to heat in vehicles while traveling through space s during time t, $V_{f,t,s}$ is the total volume (in $\mathrm{m^3}$) of gasoline equivalent fuel consumed by all vehicles traveling through space s during time t, u_{gas} is the energy density of gasoline fuel (in $\mathrm{W \cdot h \ \cdot m^{-2}}$), $VMT_{t,s}$ is the total vehicle mile traveled by all vehicles within space s during time t, $MPG_{e,s,t}$ is the weighted gasoline equivalent miles per gallon rating of all vehicles traveling through space s during time t, t is the study time period in hours, and A_s is the area of the study space s. Note that volume of fuel consumed ($V_{f,t,s}$) must be converted from gallons to cubic meters for use in equation 1. Additionally, fuel consumed by all vehicles is converted into the gasoline equivalents using standard conversions via the U.S. Energy Information Administration (EIA 2017).

2.3 Assumptions and Uncertainty

Although much data exists to aid in estimating waste heat from vehicle travel, some assumption are made when necessary.

Although the 2016 NHTS has been conducted, it has yet to be released. As a result, the best available high granularity travel data is from the 2009 NHTS. From 2009 to current, Maricopa County's population has likely increased. However, fuel consumption by household and travel time densities may not correlate directly to a population increase, although it is likely. Despite probably increases in traffic volume, it is difficult to estimate changes in trip time densities and yearly fuel consumptions. As a result, the weighted 2009 NHTS data is not adjusted to attempt to project 2016-17 travel trends.

Aggregated NHTS daily travel times exemplify an unexpected emergent behavior of survey respondents. Survey respondents were observed to report trip start and end times at convenient times, especially at times on the hour (e.g. 5pm, 10am, etc). This resulted in high spikes of trips occurring right on every hour in the data. To adjust for this discrepancy, a moving average of 25 minutes was introduced to smooth the time-of-day occurrence of trips.

Previous literature indicates that waste heat from vehicles dissipated to the ambient surroundings can range between 30% to 80% depending on assumptions, fuel type, engine type, and other factors. As the most common cited number is 'two-thirds' energy lost to waste heat, this analysis assumes 60% of fuel energy is lost to waste heat for all internal combustion engines. A ±10% buffer is included in error estimates to provide a range of uncertainty.

Although highways vary in width due to number of lanes, shoulder width, and median width, no comprehensive data exists that accurately documents Arizona highway dimensions. As a proxy for width, a constant value of 60m (200ft) is assumed. This width is chosen as it is large enough to encase even the largest sections of highways throughout County; lanes are typically 12-14 ft wide, and shoulders and medians can be between 8 – 20 feet in width.

Fleet average fuel economies are assumed to be the national yearly averages for light and heavy duty vehicles for 2015. Light duty vehicles are assumed to have a 21.7 mile per gallon (MPG) on-highway fuel efficiency. Heavy duty vehicles are assumed to have a 7.4 mile per gallon equivalent (MPGe) on-highway efficiency for single unit trucks, and a 6.0 MPGe on-highway efficiency for combo unit trucks. Single unit and combo unit trucks are separately counted in ADOT AADT data where a single unit truck has an attached static storage piece (e.g. a short U-Haul vehicle) and a combo unit truck storage is connected via trailer (semi-truck).

3 Results

3.1 Travel Density by Time of Day in Maricopa

Figure 5 shows the fraction of daily motorized trips in Maricopa County from the NHTS analysis. Multiple aggregations of the results are displayed including weighted vs. unweighted data and smoothed vs. unsmoothed data. As mentioned previously, it can be observed that survey respondents over report themselves leaving on the hour, even when appropriately weighting the data, so smoothing was necessary. The highest time for travel density is roughly between 5:00pm and 5:05pm. This coincides with the evening rush hour. There is also another local maxima for the morning peak. These results indicate that considering temporal distribution of vehicle travel is important as high fractions of travel occur during the morning and evening rush hours.

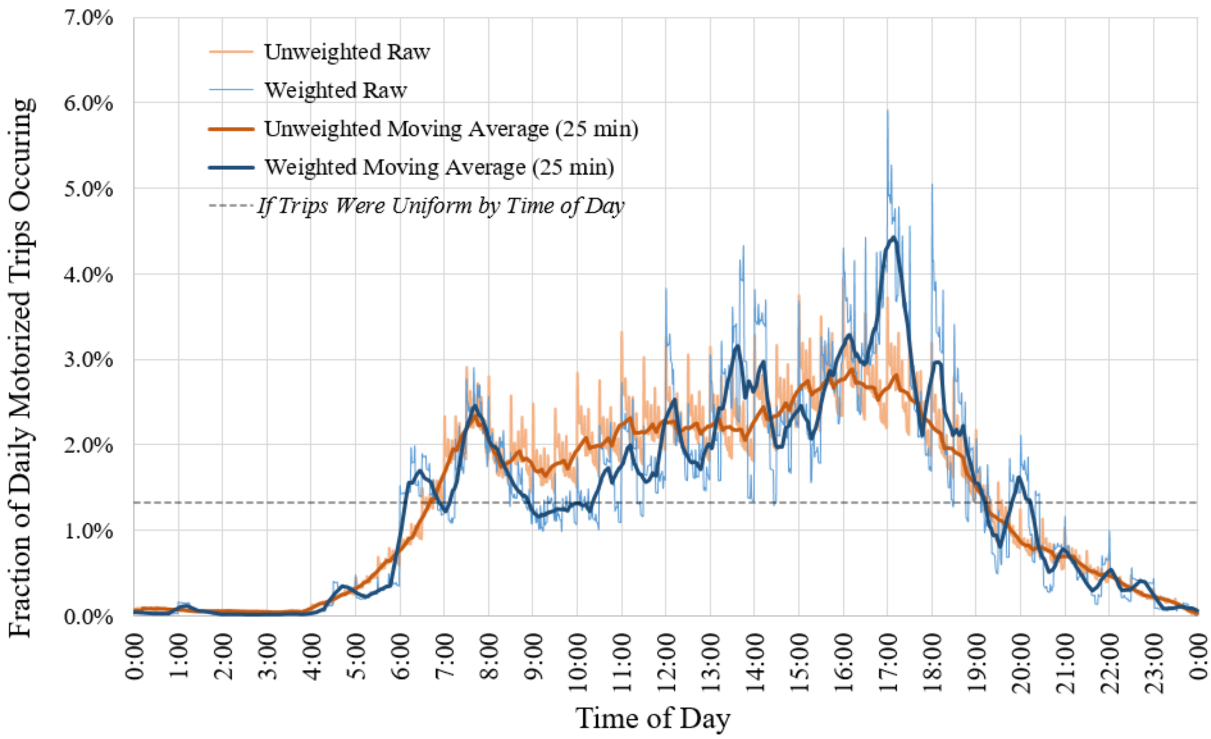

Figure 5 – Fraction of daily motorized trips in Maricopa County.
Data from the 2009 NHTS. Total trips, N = 31,654.

3.2 Vehicle Waste Heat Estimates in Maricopa

Vehicle waste heat estimates for the entire Maricopa County are shown in **Figure 6**. At the evening peak, waste heat estimates are still very small, accounting for an absolute maximum of 0.8 W/m^2. This indicates that aggregating over an entire county area is not very impactful and produces insignificant vehicle related waste heat. **Figure 7** shows waste heat estimates aggregated over only the incorporated areas in Maricopa County for vehicle travel. These results show a moderate increase from the entire county aggregation with daytime heat flux of at least 0.5 W/m^2, reaching as high as potentially 3.5 W/m^2. However, these results are still very small, and unlikely to contribute to any urban heat islands at this scale. **Figure 8** shows results aggregated over only the area enclosing the AZ 101 highway loop. At this very small scale of spatial aggregation, results jump significantly ranging from around 50 to 300 W/m^2 in the daytime. At these levels of waste heat, there could be warming due to high local heat flux. However, there may be little impact of this local warming if it is just localized to the extent of the highways. **Figure 9** shows waste heat results aggregated to a neighborhood level surrounding the high volume interchange of the I-17 and I-10 highways in south Phoenix. In this small area that includes a cemetery, waste heat from vehicle travel is estimated to be between 5 and 20 W/m^2 during the daytime.

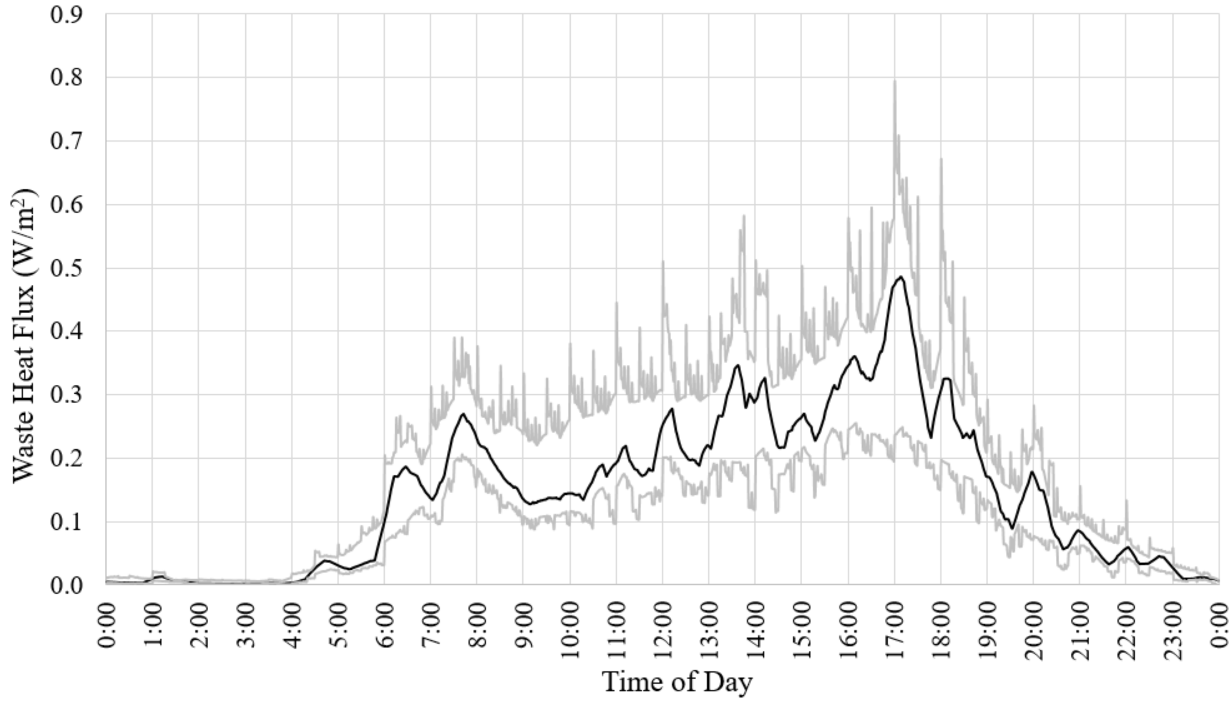

Figure 6 – Estimated waste heat flux from vehicle travel in Maricopa County over an average day.
The black line represents the average and the gray lines represent the max positive and negative error.

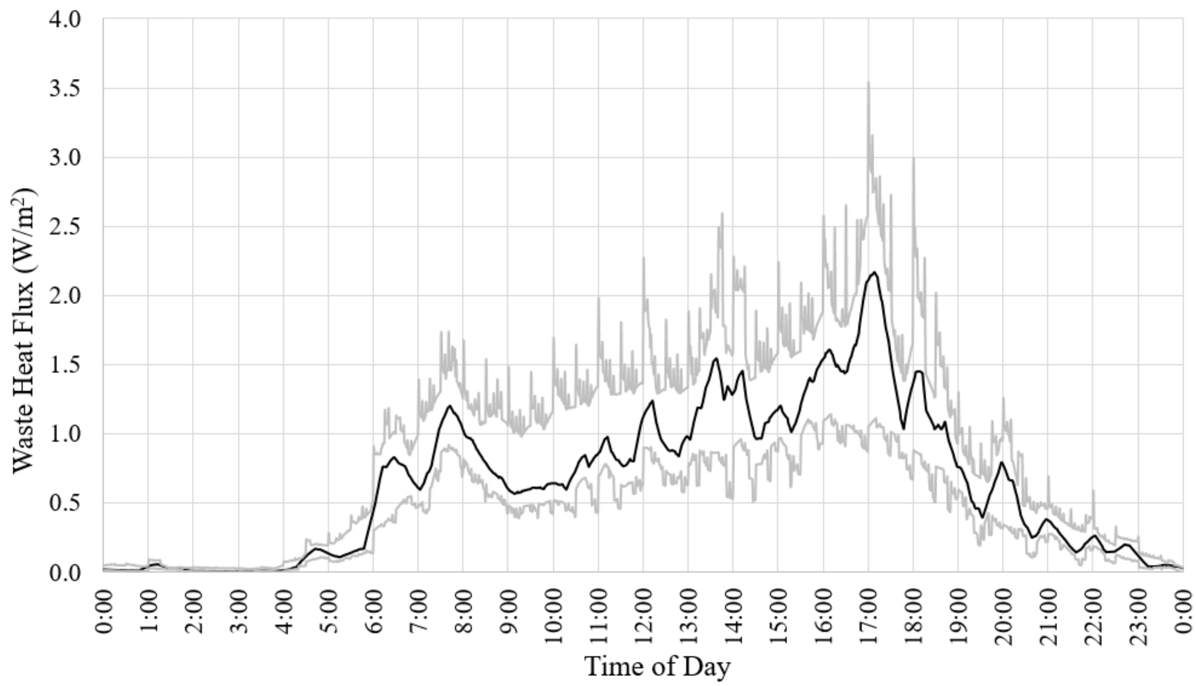

Figure 7 - Estimated waste heat flux from vehicle travel in incorporated Maricopa County over an average day.
The black line represents the average and the gray lines represent the max positive and negative error.

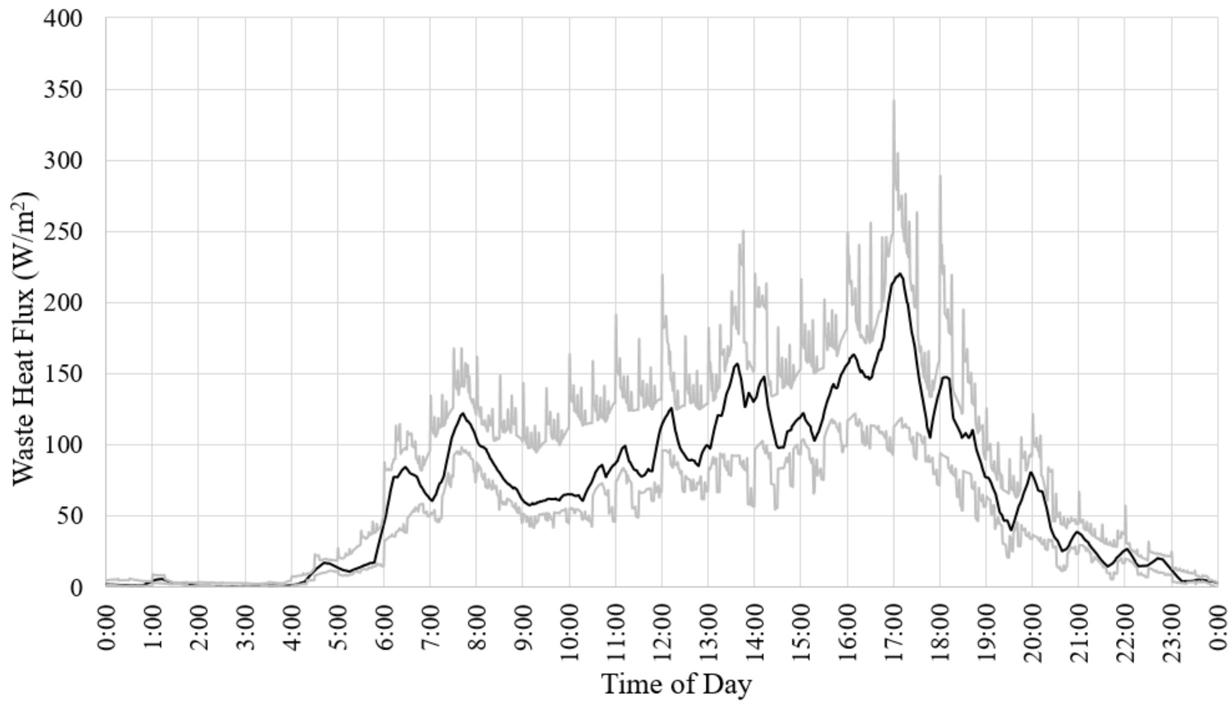

Figure 8 - Estimated waste heat flux from vehicle travel the on AZ 101 over an average day.
The black line represents the average and the gray lines represent the max positive and negative error.

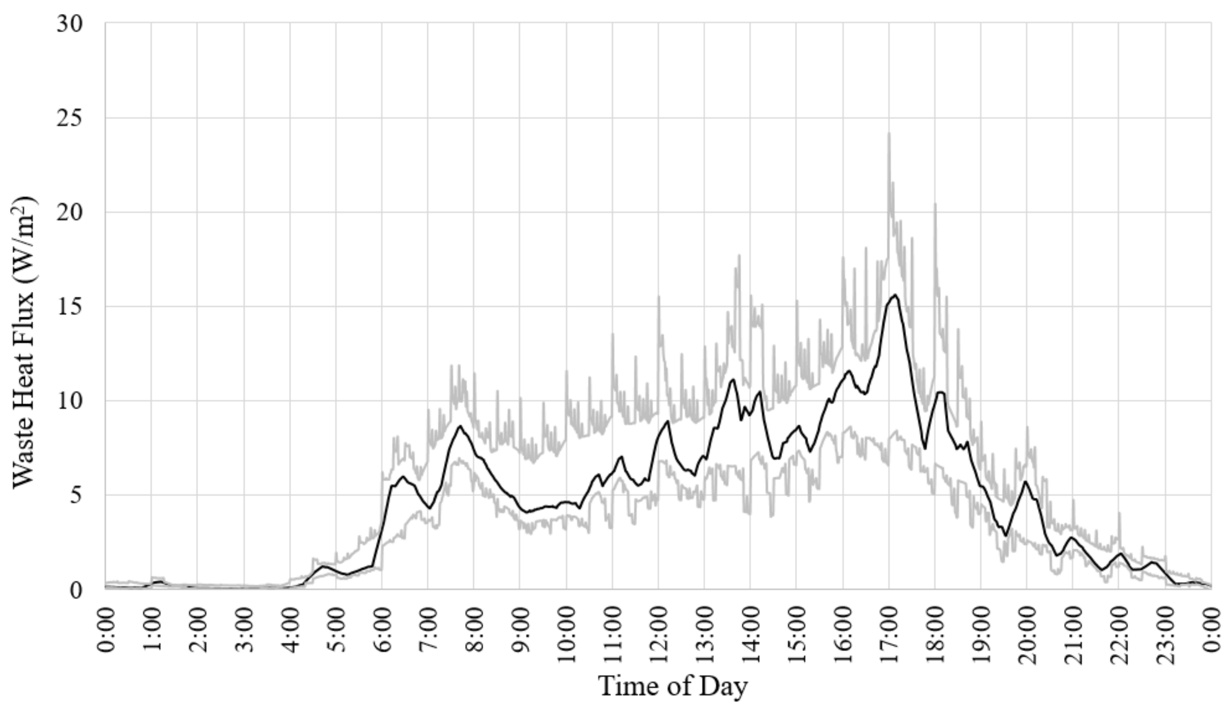

Figure 9 - Estimated waste heat flux from vehicle travel in the neighborhood surrounding the I-10 and I-17 interchange over an average day (see Figure 4 for study area).
The black line represents the average and the gray lines represent the max positive and negative error.

3.3 SCENARIOS FOR REDUCING WASTE HEAT

Five different scenarios were evaluated to test the impacts of improved vehicle efficiencies on reducing vehicle related waste heat. The scenarios and their consequent reductions are shown in **Table 1**. The first scenario targets all light duty vehicles older than 2000 model year and replaces them with the 2016 fleet average MPG. In this scenario, 31% of light duty vehicles from NHTS 2009 data replaced. For these vehicles, the average fuel economies increased from 19 MPG to 36 MPG. Although this seems like a substantive replacement, waste heat is only reduced by 11% across the region. In the second scenario, all light duty vehicles from the NHTS are replaced with 2016 MPG fuel economies. This improves all vehicles fuel efficiencies from around 22 MPG to 36 MPG and reduces nearly a third of all waste heat from automobiles. This is a more significant reduction, but is nearing an unachievable amount of fuel economy improvements for a near future scenario. The third and fourth scenarios involve doubling MPGe of heavy duty and transit vehicles. As transit vehicles make up only around 1% of the total regional vehicle miles traveled, it is no surprise that there is a similarly small impact on reduced waste heat (also 1%). Doubling heavy duty vehicle MPGe can cause a moderate reduction of waste heat on highways, especially those with higher truck traffic per day. However, doubling the fuel efficiencies of heavy duty vehicles is extremely unrealistic because over the last few decades, heavy duty vehicle efficiencies have remained very stable. The last and most extreme scenario involved converting the entire light duty fleet to a 100% electric fleet with 110 equivalent MPGe. As electric vehicles have no fuel combustion, they have no waste heat from exhaust. It was therefore assumed that only 20% of energy used was lost to waste heat. As a result of the significant improvement in energy efficiency, there was a very large reduction in total waste heat from vehicles. Although this scenario is extremely unlikely in the near future, it could be possible many decades from now.

Table 1 - Waste Heat Reduction Scenarios and Results

Reduction Scenario	Total Waste Heat Reductions
Replace all light duty vehicles older than 2000 year model year with 2016 MPG	11% across region
Replace all light duty vehicles with 2016 MPG	32% across region
Double all MPGe of all heavy duty vehicles	7% across region 10% to 28% on highways
Double all transit vehicle MPGe	1% across region
Convert the entire light duty vehicle fleet to 100% electric	67% across region 77% to 89% on highways

4 DISCUSSION

Vehicle waste heat has been documented to be a potentially significant contributor to anthropogenic waste heat if examined at small spatial scales, but practically inconsequential at larger spatial scales. From this study, vehicle realated waste heat at very large scales such as the county or city level is unlikely to make any significant contributions to anthropogenic waste heat. However, at smaller scales during peak hours - like around high density interchanges or intersections - high estimates of waste heat may be occurring that could potentially influence local climate. At the highest level (on highways), there is likely little very close pedestrian traffic or other human outdoor activities. However, at the neighborhood scale around a major highway interchange, vehicle waste heat has potential to influence local climate. Also, considering parks and lower quality housing can be located very close to major highways, social inequity issues could be argued if highway vehicle waste heat is confirmed significant and impacts local climates. Some previous research has shown that anthropogenic heat increases by 100 W/m^2 could translate to around a 0.3 C increase in average surface air temperature in Taipei (Lin et al. 2008). This shows that there is certainly potential for high density vehicle travel to affect local temperatures.

Scenarios tested for reducing waste heat show that significant improvements in vehicle fuel efficiencies are necessary to make any measureable impacts. Furthermore, it is unlikely that any of the extreme scenarios will be reached in the near future (100% electric, doubling MPGe). As a result, reducing waste heat through improved fuel economies and increased electric vehicle fleet penetration will only be a minimal benefit and should not be a major priority on its own. Decades into the future, autonomous technology and further technological improvements of vehicles could lead to an urban environment with very little vehicle waste heat.

It is clear that more research in this space could be done. More up-to-date data, including advanced macro traffic simulations could provide more evaluation of dynamic changes of waste heat over space and time. Additionally, case studies could be implemented to evaluate and validate if specific neighborhoods could have local warming effects due to high volume nearby traffic from highways.

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APPENDIX

The following shows the units for each factor in equations 1 and 2:

$$\phi_{q,t,s} = Q_e * V_{f,t,s} * u_{gas} * t^{-1} * {A_s}^{-1} \tag{1}$$

$$\left(\frac{W}{m^2}\right) = (\%) * (m^3) * \left(\frac{Wh}{m^3}\right) * (m^{-2}) * (h) \qquad \textit{units}$$

$$V_{f,t,s} = VMT_{t,s} * {MPG_{e,s,t}}^{-1} \tag{2}$$

$$(gal) = (miles) * \left(\frac{miles}{gal}\right)^{-1} \qquad \textit{units}$$