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# Protecting People in Midwest Road and Transport Systems During Periods of Extreme Heat


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16. Abstract: Extreme heat events have impacts on road transit systems. The primary impact is through heat stress on motorists, construction and maintenance crews, and public safety personnel. Heat stress effects are strongest on sensitive subgroups, including infants, children, the elderly, pregnant women, and those with preexisting medical conditions. Heat is associated with decreased driver performance and increased emergency service calls and can interfere with road surface integrity and vehicle operation. Extreme heat also poses challenges to transport of animals in the region. Extreme heat increases transit system pollutant emissions in multiple ways, including increased particle emissions from tires and road wear, increased organic compound emissions from off-gassing asphalt and plastics, and increased fuel use. Pavement and near-road air temperatures and heat indices (which can include humidity, or humidity, wind and solar radiation) can be estimated throughout the Midwest using a combination of in situ measurements and estimated environmental parameters from public databases. Downscaled global climate models indicate that the intensity and number of extreme events will increase in coming decades. Historical data and future projections indicate that daytime temperature-humidity heat indices will increase more rapidly than temperature alone. Satellite remote sensing, combining high spatial resolution visible imagery with lower spatial resolution multispectral imagery, can estimate road surface temperatures at seasonal average timescales.

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List of Abbreviations

Mid-America Transportation Center (MATC)
Nebraska Transportation Center (NTC)
Extreme Heat Event (EHE)
Electric Vehicle (EV)
Heat Response Plan (HRP)
Iowa Environmental Mesonet (IEM)
Individually Experienced Temperature (IET)
Hot Mix Asphalt (HMA)
National Aeronautics and Space Administration (NASA)
National Weather Service (NWS)
Occupational Safety and Health Administration (OSHA)
Prediction Of Worldwide Energy Resources (POWER)
Personal Protective Equipment (PPE)
Roadway Weather Information System (RWIS)
Urban Heat Island (UHI)
State Highway Research Program (SHRP)

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Abstract

Extreme heat events have impacts on road transit systems. The primary impact is through heat stress on motorists, construction and maintenance crews, and public safety personnel. Heat stress effects are strongest on sensitive subgroups, including infants, children, the elderly, pregnant women, and those with preexisting medical conditions. Heat is associated with decreased driver performance and increased emergency service calls and can interfere with road surface integrity and vehicle operation. Extreme heat also poses challenges to transport of animals in the region. Extreme heat increases transit system pollutant emissions in multiple ways, including increased particle emissions from tires and road wear, increased organic compound emissions from off-gassing asphalt and plastics, and increased fuel use. Pavement and near-road air temperatures and heat indices (which can include humidity, or humidity, wind and solar radiation) can be estimated throughout the Midwest using a combination of in situ measurements and estimated environmental parameters from public databases. Downscaled global climate models indicate that the intensity and number of extreme events will increase in coming decades. Historical data and future projections indicate that daytime temperature-humidity heat indices will increase more rapidly than temperature alone. Satellite remote sensing, combining high spatial resolution visible imagery with lower spatial resolution multispectral imagery, can estimate road surface temperatures at seasonal average timescales.

# Chapter 1 Effects of High Heat on Road Transit

US transportation infrastructure requires significant increases in resilience to periods of extreme heat. Periods of extreme heat (as well as the related conditions of higher dew points and higher solar insolation) are increasing. While daytime extreme temperatures in the Midwest have decreased slightly in recent decades, maximum daytime heat indexes have been stable. Both are anticipated to increase in coming decades. Retrofits, operational adaptations, and changes to new construction are all needed to prevent economic disruption and health effects from extreme heat.

Extreme heat events (EHE) can occur in conjunction with other stresses on the transportation system to create compound events. These include

- Extreme heat events plus air pollution
- Extreme heat events plus fire or smoke
- Extreme heat events plus power outage
- Extreme heat events plus drought
- Extreme heat events plus atypical transportation patterns (evacuations; natural disaster; chemical, biological or nuclear release; derailment; bridge failure; downed trees; etc.)
- Back-to-back EHE (alternately referred to as temporally compound heat wave)

The effects of high temperature on road transportation were assessed through a literature review. These effects are the justification for the analysis of roadway pavement temperatures, and near-roadway environmental conditions (temperature, relative humidity, solar radiation) necessary for the computation of various heat stress indices that can be used for assessing and communicating risk and recommended preventative measures to stakeholders including road workers, public safety workers, and the travelling public.

The effects are listed in Table 1.1 and discussed in the text.

Table 1.1 Tabular Summary of Impacts of High Heat on Road Transit Systems

| Category and Impacts | | Citations |
|---|---|---|
| | | |
| Heat stress | | |
| | General heat stress risk increase for people (i.e., transport system users, police, construction workers, first responders) | (Ebi et al., 2021; Luber & McGeehin, 2008; NIOSH, 2016; OSHA, 2024) |
| | Heat stress risks for motorists experiencing delays (traffic stoppage for extended period of time) or stranded motorists | |
| | Heat stress for those without vehicle air conditioning and/or sensitive groups (infants, pregnant mothers, young children, elderly, preexisting health conditions) | (Luber & McGeehin, 2008) |
| | Risks for those left unattended in enclosed vehicles (i.e., children, pets) | (McLaren et al., 2005) |
| | Risks for transported animals: livestock, horses, and poultry | (Brindle, 2016; Lacetera, 2019) |
| | Challenges for road construction crews (productivity loss, enhanced monitoring and protective workplace actions) | (Han et al., 2024; NIOSH, 2016; OSHA, 2024; Specht et al., 2024) |
| | Increased emergency services calls | (Behrer & Bolotnyy, 2024; Williams et al., 2020) |
| Vehicle and Engine Issues | | |
| | Decreases in power and torque | (Husaboe, 2013) |
| | Increased incidence rate for mechanical problems due to engine overheating, coolant breakdown, and component failure associated with high temperature or high load | |
| | Increased engine wear due to engine oil viscosity changes and/or components operating at or above temperature design specs | |
| | Lower vehicle fuel economy (primarily associated with increased air conditioning use) | |
| | Increased incidence rate of vehicle fires (internal combustion engines) – associated with overheating | |
| | EV battery effects (fire risk; faster loss of charge) | |
| | Increased air conditioner use | |

| | | |
|---|---|---|
| Transport infrastructure and road performance | | |
| | Road failure (i.e., buckling) | (Ham, 2024) |
| | Other thermal expansion-related damage or capacity reduction | (Ham, 2024) |
| | Asphalt surface flushing / bleeding / rutting leading to skidding & increased maintenance | (Smoyer-Tomic et al., 2003) |
| | Problems in curing concrete properly when conditions too hot/dry | (Smoyer-Tomic et al., 2003) |
| Performance, wear, and dust emissions issues with brakes, tires, and road wear | | |
| | Increased stopping distance due to tire and brake performance | |
| | Increased tire wear particle emissions and changes in the emitted size distribution | (Costagliola et al., 2024; Schläfle et al., 2023) |
| | Increased blowout risk from tire overheating, tire pressure increase, and/or high temperature exacerbating existing tire defects | (Smoyer-Tomic et al., 2003) |
| | Increase in fine and ultrafine particle emissions from brakes operating above critical temperatures for emission of volatile components | (Costagliola et al., 2024) |
| | Increased road wear rate | (Bae et al., 2024; Costagliola et al., 2024) |
| Other driving safety issues | | |
| | Effect on driver performance. (Distraction, cognitive function, fatigue, increased reaction time). | (Daanen et al., 2003; Gariazzo et al., 2021) |
| Other emission effects | | |
| | Increased emissions from increased fuel usage | |
| | Evaporative fuel and permeation emissions | |
| | Off-gassing of organic compounds from outdoor polymer materials at high temperature (asphalt, coatings and sealants) | (Khare et al., 2020; Kriech et al., 2022) |
| | Off-gassing of organic compounds from vehicles into the vehicle cabin and near-road environment | (Wang et al., 2023) |

## 1.1 Heat Stress

EHE as a public health threat are well-studied and well-documented. In an epidemiological analysis for North America, heat-related deaths slightly outnumber cold-related deaths; furthermore, the incidence rate of heat-related deaths is increasing while that of cold-related death is decreasing (Zhao et al., 2021). In climates such as those experienced in Iowa, severe winter weather claims more lives in transportation-related incidents (Smoyer-Tomic et al., 2003). However, transportation heat-related challenges are increasing and expected to continue increasing as frequency of EHE increases due to climate change (Hayhoe et al., 2010; Schoof et al., 2015).

Heat stress manifests itself primarily through heat exhaustion, heat syncope (brief fainting spell or feeling of dizziness caused by heat exposure), and heat stroke. Heat stress is not just the result of high temperatures but occurs from a combination of factors related to the balance of heat loss from the body, internal (metabolic) heat generation, and heat input from radiation and other heat transfer mechanisms from the environment. Relative humidity (influencing the ability to cool oneself through sweating), hydration, electrolyte management, wind, and sun are critical factors in heat stress management.

Death and illness during EHE are largely preventable. At the community level (in other words, extending to all parts of society and not restricted to transportation systems), reducing the health burdens of EHE occurs through heat action plans, early warning systems, public cooling shelters, targeted messaging, wellness checks, and water distribution. One needs to make sure at-risk individuals have access to transportation and medical care. Land use, road design, and urban planning can be used to manage urban heat island effects and provide shade. Prevention activities are typically classified as passive (not requiring action from at-risk individual) or active (requiring action). They are further classified as primary (preventing illness), secondary (early detection and intervention), and tertiary (restoring ill people to health after the EHE). Survivors of heat stroke can have significant medical issues after partial recovery (Ebi et al., 2021; Luber & McGeehin, 2008; OSHA, 2024; Smoyer-Tomic et al., 2003).

Those who work on Iowa's roadways (police, state troopers, construction and maintenance crews) experience similar EHE risks as the public, plus distinct factors related to occupational exposure to heat and the need to wear significant personal protective equipment (PPE). First responders are a critical part of heat response plan (HRP) implementation.

Heat may be a factor in managing stranded motorists and managing groups of delayed motorists during extended backups. Heat stress is more serious for those in sensitive groups: infants, pregnant mothers, young children, elderly, and preexisting health conditions. Furthermore, lack of air conditioning while driving is an additional risk factor. Risk factors can also be combined (sensitive group and lack of air conditioning) (Luber & McGeehin, 2008).

Enclosed vehicles are particularly dangerous for pets and children. An EHE is not required to make an enclosed vehicle dangerous, but the time available for rescue will be the shortest during EHE, particularly during sunny days. In experimental tests with enclosed vehicles during sunny days, vehicles quickly reached temperatures of 56.7 to 67.8°C (134 to 154°F). Even on a cool (22°C, 72°F) day, an enclosed vehicle could quickly reach 47.2°C (117°F). Eighty percent of the temperature rise occurs in the first 30 minutes (McLaren et al., 2005).

Public warnings regarding EHE and mitigation measures (having water in the vehicle, having a full tank of gas, etc.) may help reduce the need for emergency assistance. One example warning statement for drivers during EHE is from the Georgia State Patrol.[1] It includes:

- Tire pressure check
- Check of wiper blades for brittleness
- Visual check of hoses and belts

[1] https://dps.georgia.gov/state-patrol-warns-summer-heat-dangers-0?form=MG0AV3

- Never leave children or pets in an unattended car
- Teaching kids that cars and trucks are not play areas
- Lock vehicles to prevent kids from playing in them
- Emergency kit including flashlight, first-aid kit, water and other items

In the Midwest, animals including livestock, poultry, and horses, are transported. In the U.S., fifty million cows, sheep, and pigs and over nine billion turkeys and chickens are slaughtered for food annually, and most undergo transport to slaughter, and at other times in their life cycle (e.g., from birthing in one state, to finishing in another location, and slaughter at a third location). Seeing tractor trailers with loads of pigs or cattle is a common occurrence in the region. These animals are susceptible to heat, given the close quarters in transport vehicles, lack of air movement, lack of air conditioning, lack of shade along many roadways and parking areas, and metabolic heat generated from the animals. The average death rate for pigs in transport is 0.6% and this is increased during periods of extreme heat or cold (Brindle, 2016; Lacetera, 2019).

EHE cause on-farm problems for livestock and poultry, which are beyond the scope of this document. Transport is governed by the “28-hour law” (which limits confinement time without unloading for watering and feeding, 49 U.S. Code § 80502) and supplemented by heat indices such as the Livestock Temperature Humidity Index. Heat indices for specific species can be found at the National Weather Service, State Governments, and trade associations. These typically combine temperature and humidity into a heat index and include four categories: normal, alert, danger, and emergency levels. Each level has recommendations on managing heat stress for animals in transport, such as reducing the density of animals in confinement and providing mechanical ventilation if stopped. If livestock or poultry arrive for slaughter appearing exhausted or dehydrated, or dead from heat stress, this may lead to investigation initiated by USDA inspection program personnel (Brindle, 2016; St-Pierre et al., 2003).

EHE present particular challenges for road construction and maintenance crews. In fact, highway workers are 13 times more likely to die from heat related illnesses than other occupations. The combination of physical activity, sun exposure, personal protective equipment, and radiation from hot road surface and machines create heat stress challenges. The result can be acute heat injuries, productivity loss, and chronic health conditions (kidney disease exacerbated by dehydration). EHE triggers requirements for enhanced monitoring of weather conditions and worker health and triggers the need for workplace protective actions (e.g., time limits including differentiation for unacclimatized workers, water, breaks, electrolyte management, shade, etc.). Research shows that workplace accidents are more prevalent during hot days, and that unacclimatized, female, and older workers are more susceptible to heat stress (Han et al., 2024; NIOSH, 2016; OSHA, 2024; Specht et al., 2024).

Heat stress is also an issue for emergency responders, including police, state troopers, firefighters, and emergency medical service personnel. Exposure, lack of shade, inability to take breaks during emergency response, heavy gear and clothing, and exertion raise the risk of occupational heat stress. In addition, there is a slight increase in emergency service calls on days with extreme heat. Extreme heat has been linked to increased crime rates, impulsive behavior, and cognitive impairment (Behrer & Bolotnyy, 2024; Gubernot et al., 2015; Lewis et al., 2023; Williams et al., 2020).

### 1.2 Vehicle and Engine Issues

At high ambient temperatures, internal combustion engines experience a slight decrease in power and torque from decreased oxygen intake. This is caused by the decrease in air density at high temperatures. Under hot and humid conditions, the density effect is supplemented by a dilution effect where water vapor displaces some of the nitrogen and oxygen, further reducing oxygen flow to the engine (Husaboe, 2013).

High ambient temperatures cause an increase in mechanical and engine problems, including overheating and component failure (from high temperature or high load, or both). Coolant breakdown can occur at higher temperatures. Engine oil is reduced in viscosity at high engine temperatures, and this in turn can increase engine wear. High temperatures change fuel volatilization behavior as well.

Since overheating is one contributor to vehicle fires in internal combustion engines, and high temperature may stress hoses and cause leaks, EHE may have a slight increase in vehicle fire incidence rates. However, the main factors for vehicle fires are fuel system leaks, electrical failures, and spilled fluids, which are mostly independent from EHE. Many of the aforementioned effects will be negligible in new vehicles but may be more serious in older vehicles.

In the absence of increased air conditioner use, vehicle fuel economy stays approximately constant, aided by reduction in drag from less dense air at high temperatures. However, when increased air conditioner use is factored in, fuel economy decreases during hot weather (EPA, 2022).

The performance of electric vehicles (EV) during EHE has not been thoroughly studied and is evolving as battery technology and battery and vehicle control systems advance. EV batteries have an optimal temperature range for operation and have been shown to have faster loss of charge under hot conditions. EV battery thermal runaway (the initial stage of an EV battery fire) may be more likely during an EHE because system cooling is more difficult in general. However, the main cause of thermal runaway is defective or damaged (i.e., in vehicle collision) cells, which are unrelated to EHE. During hot and sunny weather, EV chargers and batteries undergoing charging will run hotter, and may trigger design limits and safety interlocks or automatic reductions in the rate of charging. During EHE it is recommended to maintain EV battery charge at 20-80% if practical, and to charge in the shade.

### 1.3 Transport Infrastructure and Road Performance

Extreme heat can damage road surfaces and other transportation infrastructure. In jointed concrete, buckling can occur. In asphalt road surfaces, flushing, bleeding, and rutting can occur during hot, sunny, and/or moist conditions. Thermal cracking may occur which then permits moisture entry, decreasing lifetime and increasing maintenance requirements (Adwan et al., 2021; Ham, 2024; Smoyer-Tomic et al., 2003).

Other thermal expansion-related damage or capacity reductions can occur. One dramatic example is the inability to move a swing bridge in New York City during a period of high temperatures. Another area where high heat can cause problems with road transport is in proper concrete cure, especially if conditions are dry in addition to hot (Almusallam, 2001; Ham, 2024; Smoyer-Tomic et al., 2003).

### 1.4 Performance, wear, and dust emissions issues with brakes, tires, and road wear

When tires and roads are hot, there may be increased stopping distances due to lower performance of both tires and brakes. The increase in tire pressure from hot conditions contributes to this, decreasing the surface area of contact with the road. Changes in tire hardness also contribute. On the braking side, there is an increase in the probability of brake fade under high road and ambient temperature conditions. One should note that while ambient temperatures influence brake temperatures, they are not the main influence; other factors such as braking frequency, pressure, and conditions of the braking surfaces predominate. At brake temperatures below 300°C (572°F), mechanical friction abrades brake surfaces, creating brake dust which can be suspended and breathed as fine and coarse particulate matter. Non-asbestos organic (NAO) pads, more prevalent in the US and Asia, tend to have lower emission factors at these lower temperatures, while low metallic (LM) pads, more common in Europe, have higher emissions (Costagliola et al., 2024; Woo et al., 2022).

As temperatures rise, semivolatile gases can be emitted from the hot braking surfaces (particularly from organic compounds present in pads); as these gaseous emissions cool, they nucleate to form ultrafine and fine particles that stay suspended in air longer and penetrate deeper into the respiratory system. The transition temperature for this nucleation and ultrafine emission process varies depending on brake material (Costagliola et al., 2024).

There has been a recent upswing in research on brake, tire, and road wear particle emissions due to the debate on the degree of fine particulate matter reduction achieved from a transition to EVs, as well as research highlighting ecotoxicity of some tire wear particles. With their higher weight and power, tire abrasion is accelerated in EVs compared to equivalent internal combustion engine vehicles. Brake emissions need further study, as higher vehicle weight will tend to increase emissions while regenerative braking can decrease break wear. While these issues are not a focus of the current project and report, they have increased the recent availability of brake, tire, and road wear particle emission estimates (Baensch-Baltruschat et al., 2020; Saladin et al., 2024; Woo et al., 2022).

Tire wear particle emissions increase at high tire temperatures, and the size distribution of the particles shifts. The increase in emissions is attributed to softening of the tire. The size distribution of emitted particles shifts to larger particles at higher tire temperature. This has been demonstrated with summer, winter, and all-weather tires. As with brakes, ambient and road temperatures influence, but do not solely determine, tire temperature. Other factors, including tread, road conditions, wind, and vehicle speed, are also critical (Costagliola et al., 2024; Schläfle et al., 2023).

Understanding road wear particle generation is less advanced than that of tire wear particle generation. Studies show correlation between tire and road wear, with high tire wear rates occurring with high road wear rates; this is expected from the friction mechanism of generation. In most emission inventories, road wear fine particulate matter is assumed to be 1.36 times that of tire wear particle emissions. The chemical composition, size, and shape of road wear particles differ markedly for asphalt versus concrete roads. Due to the underlying mechanism of particle generation from friction, it is reasonable to anticipate an increase in emissions under hot temperatures, especially for asphalt roads (Bae et al., 2024; Costagliola et al., 2024; Woo et al., 2022).

Increased ambient temperatures are a contributing factor to tire blowouts. This is attributed to thermally generated increases in tire pressure, and exacerbation of existing defects, damage, or other points of weakness in tires at high temperatures (Smoyer-Tomic et al., 2003).

### 1.5 Other driving safety issues

Epidemiological analyses have shown a modest but significant increase in crashes during hot weather (about 1% per 1°C (1.8°F) of peak daily temperature). The effect was consistent between those driving for work and those driving for non-work purposes. Controlled driver testing studies have shown a 16% decrease in scores on standardized driving performance measures during hot weather. These types of effects have been attributed to driver distraction, cognitive function decline, poor reaction time, and/or fatigue associated with hot weather. Brake and tire performance, as well as road surface issues mentioned above, may also contribute (Daanen et al., 2003; Gariazzo et al., 2021; Gu et al., 2025).

1.6 Other effects of emissions

The increased fuel use (caused by increased air conditioner use) increases tailpipe emissions from vehicles on hot days. We should note that tailpipe emission factors (emissions per unit of fuel energy burnt) for nitrogen oxides, carbon monoxide, and total hydrocarbons do not change significantly during high ambient temperatures. The increase is due to increased fuel consumption, primarily for air conditioning. Evaporative fuel loss and fuel permeation through hoses increases with ambient temperature (EPA, 2022).

Off-gassing of consumer products and construction materials has been shown to be a major source of air pollution in some locations, particularly as traditional factory and tailpipe vehicle emissions have decreased. Road surfaces (particularly asphalt), sealants, coatings, and other outdoor polymer materials will engage in temperature- and sunlight-dependent off-gassing. This will locally enhance pollutant concentrations near roads and secondary reactions of these compounds contribute to ozone and fine particulate matter pollution (i.e., photochemical haze) on hot days (Khare et al., 2020; Kriech et al., 2022).

A similar temperature-dependent off-gassing process occurs from plastic and rubber components in vehicles. Controlled testing indicates strong correlation of vehicle cabin volatile organic compound concentrations with the surface temperatures of key surfaces such as the dashboard. Compounds detected included several with known health effects (e.g., formaldehyde, acetaldehyde) occurring at above occupational exposure limits at the highest vehicle cabin temperatures. Off-gassing is most pronounced in new vehicles, but detectable increases in volatile organics upon vehicle heating have been seen in vehicles older than ten years (Wang et al., 2023).

Emissions can be into the cabin (from interior vehicle components) or direct to roadway air (from engine compartment and exterior components). Roadway air is then used as intake air for cabin ventilation, meaning occupants are exposed to all roadway emissions (tailpipe emissions, road wear particles, resuspended soil, tire wear particles, brake wear particles, and off-gassing from vehicle interior, exterior, and road surface).

### 1.7 Chapter 1 Summary

High ambient temperatures influence many aspects of road safety, transportation management, and emission of pollutants in the roadway environment. Most of the associations are that roadways are more dangerous and higher emitting of pollutants during the hottest days. Therefore, it is important to understand the distribution of key environmental variables in the roadway environment. At a minimum, this includes pavement temperature, air temperature, solar radiation, relative humidity, and wind conditions. For managing future EHE, defining temperature or heat index metrics of concern for these variables is needed. Furthermore, the current and anticipated future distribution of these variables is needed. In other words, the current and future number and severity of EHE should be documented.

# Chapter 2 Heat Wave Occurrence and Severity in the Midwest, Including Future Projections

## 2.1 Recent Trends

The number of days with high maximum temperatures (hottest 1 hr) have decreased in the Midwest. For example, Iowa Environmental Mesonet data from Ames, Iowa shows a decrease from about five days per year with maximum temperature greater than 35°C (95°F) in 1971 to about 1.6 days per year in 2020. At the same time, nighttime temperatures, dewpoints, and summer rainfall have been increasing in the region. This has led to maximum heat indices (a combination of temperature and humidity) holding approximately constant in the region (Basso et al., 2021; Butler et al., 2018; Schoof et al., 2015).

The reason for the lack of daytime warming and lack of increase in maximum temperatures in the Midwest is the increased precipitation and increased daytime evaporation.

## 2.2 Future Projections

Downscaled global climate models simulate that the overall warming occurring over North America will outweigh the daytime cooling from hydrologic intensification and evaporation going forward. Thus, the trend described in Section 2.1 is anticipated to reverse, with maximum temperature and frequency of high temperatures increasing in the future.

Specifically, downscaled global climate models simulate increases in the number of days with maximum temperature above 35°C (95°F). Projections have this metric increasing to 15 to 30 days per year by 2050 (USGCRP, 2023), with the variation depending on the emissions scenario (i.e., 15 days with aggressive climate action, and 30 days with limited mitigation of climate forcing agents). The same projections include increases in dewpoints, such that the combined heat and humidity become oppressive more frequently. For example, the number of days with heat index exceeding 41.1°C (106°F) by midcentury is projected to be 5 to 15 days per year (NCA5). Simulations show that Chicago could experience a heat wave like the 1995 heat wave from 0.5 to 3 times per year, with the range depending on the emission scenario (Hayhoe et al., 2010). Simulations further show an increase in the June-July-August maximum temperature by 2.3°C (4.1°F) and maximum heat index by 2.6°C (4.7°F) at midcentury (Hayhoe et al., 2010; Schoof et al., 2015). Another metric is the average daily maximum temperature of the hottest five-day period of the year. This was about 33.3°C (92°F) in Iowa for the period 1976-2005 and is predicted to go to about 36.7°C (98°F) (depending on the emission scenario) at mid-century (USGCRP, 2018).

These values are for background locations not affected by urban heat island effects. It should be noted that the analysis above focuses on daytime maximum values of temperature and heat index as those are thought to be most relevant for transportation applications. However, there is observational evidence corroborated by climate simulations for warmer and more humid summertime nights in the region, with continuation of these trends going forward due to climate change. These are relevant to the transportation system at night, including nighttime road work activity.

# Chapter 3 Metrics for Heat Wave Characterization in the Context of Road Transit

Metrics needed for decision support regarding EHE impacts are discussed in Chapter 1. Metrics need to be consistent with available data from public resources such as the Iowa Environmental Mesonet, the Roadway Weather Information System (RWIS), databases such as NASA's POWER (Prediction Of Worldwide Energy Resources), and the available future climate projection data sources such as the NASA Global Daily Downscaled Projections (CMIP6) tool (Thrasher et al., 2022).

We have reviewed the impacts from Chapter 1 and the available data from the resources listed above and propose the following metrics for calculation of current and future heat stress in road transit applications.

With the exception of the minimum daily temperature, these metrics focus on daytime conditions. Corresponding metrics for nighttime heat stress can also be calculated and will be considered based on reviewer and stakeholder feedback going forward.

Many of our analyses use the RWIS pavement temperature. According to Tina Greenfield at Iowa DOT, most of the pavement sensors are Lufft model IRS31Pro-UMB.[2] Greenfield clarified the housing and installation process as follows: "The sensor housing is similar to an epoxy and is usually colored gray to match the surrounding pavement material. The thermistor itself is imbedded in the sensor housing, about 0.1 to 0.2 inches below the surface—meaning that there is a little epoxy overtop the thermistor to protect it from plowing and traffic." Some pavement sensors measure via remote infrared and are not installed in the pavement at all. The

[2] https://www.lufft.com/products/road-runway-sensors-292/intelligent-passive-road-sensor-irs31pro-umb-2306/

Iowa DOT also operates sensor arrays that are buried, with sensors at about 1” depth, and then every three inches until 18” depth, and then every six inches until 72” depth.

Photos of the Lufft sensors, from the Lufft website, illustrate the sensor geometry relative to the road.

Figure 3.1 Pavement Sensor Closeup (credit: Lufft)

Figure 3.2 Pavement Sensors Relative to Road (credit: Lufft)

Table 3.1 Metrics Relevant to High Heat in Road Transit

| Metric | Units | Note or Citation |
|---|---|---|
| *Metrics that can be calculated for any averaging period. Based on the available data and the transportation application, these will typically be calculated at 1-hour time resolution.* | | |
| Temperature (i.e., Dry Bulb Temperature) | °C | |
| Heat Index[3] | °C | (Anderson et al., 2013) |
| Human Thermal Comfort Index | $W/m^2$ | (Harlan et al., 2006) |
| Dew Point | °C | |
| Wet Bulb Globe Temperature | °C | NWS / OSHA / (Dimiceli et al., 2011) |
| HeatRisk | 0-4 | NWS |
| Livestock Temperature Humidity Index | °C | (St-Pierre et al., 2003) |
| | | |
| *Metrics typically calculated over a longer period, such as 24-hour.*[4] | | |
| Mean Temperature | °C | (Hondula et al., 2021) |
| Max 1-hr Temperature | °C | (Hondula et al., 2021) |
| Min 1-hr Temperature | °C | |
| Exposure Period | min | (Hondula et al., 2021) |
| Degree minutes above threshold | °C-min | (Hondula et al., 2021) |
| Percentage of time above threshold | Ratio | (Hondula et al., 2021) |
| Heating degree day | Degrees °F days | (Carpio et al., 2022) |

[3] https://www.osha.gov/sites/default/files/publications/OSHA4185.pdf has heat index classifications. Caution (80°F – 90°F HI); Extreme Caution (91°F – 103°F HI); Danger (103°F – 124°F HI); Extreme Danger (126°F or higher HI).

[4] Climate Change in the Midwest has a data completeness check for hourly data used to calculate daily data. One hour in each of the 6 4-h periods of the day must be valid. For a "summer" to be valid, 90% of the days of that summer had to have valid daily statistics. Page 148.

| **Metric** | **Units** | **Note or Citation** |
| --- | --- | --- |
| CUM_HEAT (similar to degree minutes above threshold above) | Degree-days | (Niyogi & Mishra, 2013) |
| *Metrics involving event duration or using specific averaging periods* | | |
| Average maximum daily temperature over the hottest 5-day period of the year | °C | (USGCRP, 2018) |
| Heat Wave (CDC definition) | Binary | Three or more consecutive days with maximum temperature of 32.2°C or higher. |
| Warm Spell Duration Index | Count of days | (Lee et al., 2011) |

# Chapter 4 Sample Results on Midwest Pavement and Environmental Variables

## 4.1 Estimation of Pavement Temperature from Environmental Variables

Many pavement temperature models have been proposed in the literature. Adwan et al. reviewed 38 pavement temperature models, falling into three classifications: numerical simulation, analytical solution of heat transfer equations, and statistical models. Statistical models (12 reviewed in Adwan et al.) are the most relevant for this project. Having an extensive database of pavement temperature measurements from the Iowa mesonet RWIS, one may assess accuracy of available statistical models in the region, especially during hot (sunny) summer days (Adwan et al., 2021). If accurate, such models can be used to spatially extend measurements (combined with spatially continuous environmental data, such as from the NASA POWER database). Alternately a Midwest-specific regression or machine learning model could be constructed for the same purpose.

A widely cited pavement temperature model is that of Diefenderfer et al. (2006). It predicts daily maximum and minimum pavement temperature using hourly maximum (minimum) temperature, wind speeds, depth in pavement, and daily integrated solar radiation (i.e., in $kJ/m^2$). It is a linear regression model. The solar radiation is typically calculated from geographic coordinates, day of year, and solar zenith angle, and is thus a cloud-free solar radiation value. The model is validated at pavement depths of 2.5 cm to 18 cm. The model underpredicts pavement temperature on the hottest day of year by 5°C (9°F) in Virginia (where it was trained), by 5°C (9°F) in Connecticut, and 10°C (18°F) degrees in Texas. The linear nature of the regression combined with using only clear sky solar radiation is likely the cause of the underprediction. Peak temperatures were 62°C (144°F) in Texas, 54°C (129°F) in Connecticut, and 54°C (129°F) in Virginia. The main purpose of the model is for temperature estimation to select suitable asphalt binder performance grade in HMA applications. Research shows that cloud cover can modulate pavement temperature by about 10°C (18°F) (Diefenderfer et al., 2006; Walker & Anderson, 2016).

4.2 Sample Graphs of Environmental and Pavement Temperature and Environmental Variables

University of Iowa graduate student Okoye, in collaboration with graduate student Wang, performed exploratory data analysis with data from the Iowa Environmental Mesonet (IEM), the Roadway Weather Information System (RWIS), and the NASA Prediction Of Worldwide Energy Resources (POWER) database. Quality control checks by the principal investigator (Stanier) are ongoing.

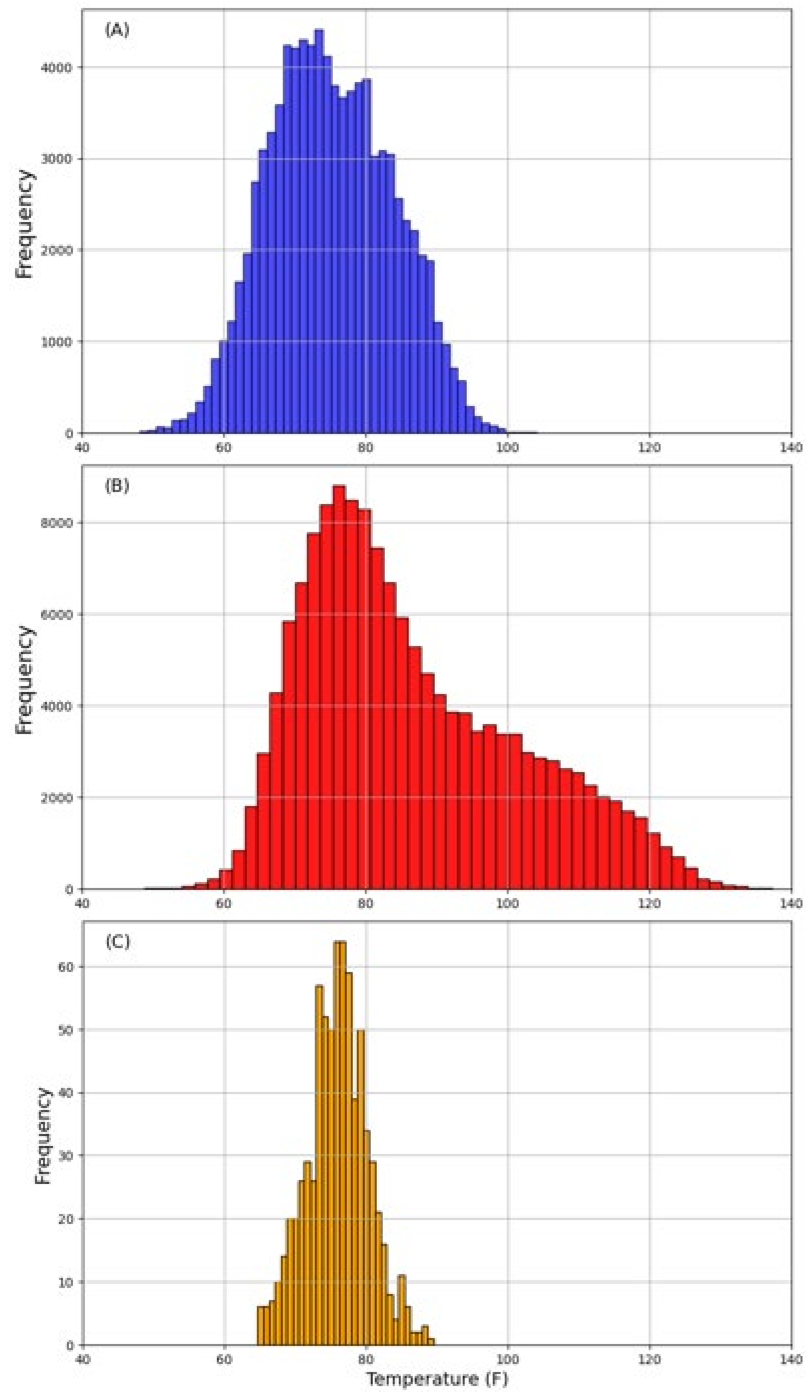


Figure 4.1 Summertime distribution of (A) air temperature; (B) pavement temperature; and (C) soil temperature from sensors in Des Moines, IA.

Figure 4.1 shows that air temperatures in Des Moines peak at around 37.7°C (100°F) (with a few datapoints reaching 107°F); pavement temperatures peak around 60°C (140°F), and soil temperature stay much cooler. Road temperatures, on average, are about 8°C (15°F) hotter than air temperature, and peak at values in the 57-60°C (135-140°F) range. Figure 4.1–4.5 show expected data features for temperature, moisture, and heat indices. Figure 4.2 shows the known hot summer of 2012. Figure 4.3 shows dry years in 2006, 2012 (most states) and 2020 and 2022 (Iowa), consistent with other records of rainfall and drought occurrence in the region. As expected, Nebraska and Kansas are the driest states while Missouri is the rainiest state. Figure 4.4 shows that, in Iowa, the hottest air temperature recorded at the Des Moines station was approximately 40°C (~104°F) and the coldest was approximately -37°C (-35°F). If outlier hours are ignored, Figure 4.5 shows the expected ranking of heat indices, which are Missouri > Illinois > Iowa > Kansas > Nebraska.

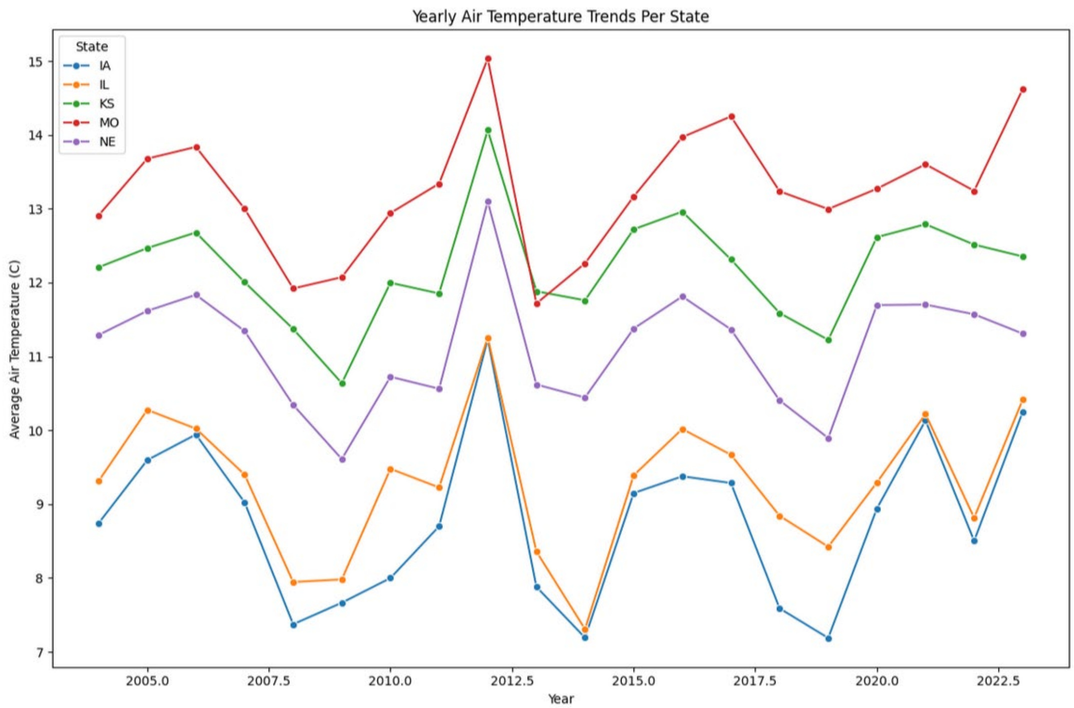


Figure 4.2 Average of Hourly Temperature Data for Iowa, Illinois, Kansas, Missouri, and Nebraska (2004 – 2023).

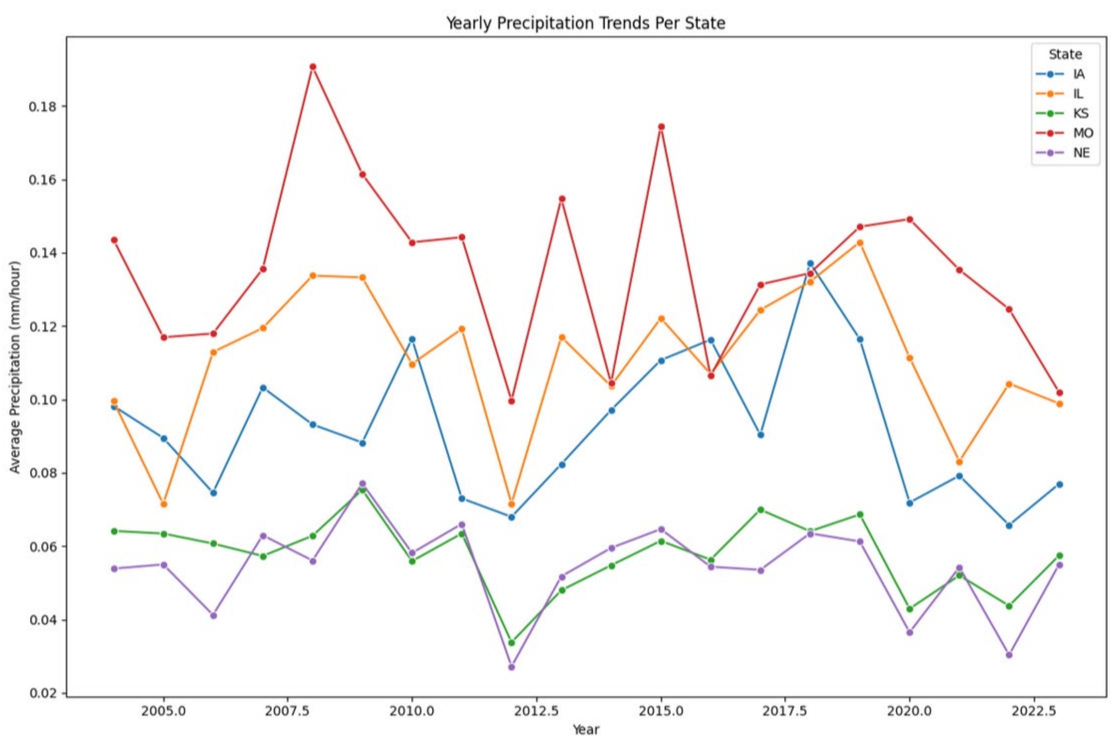


Figure 4.3 Average of Hourly Precipitation Data for the Five-state Area.

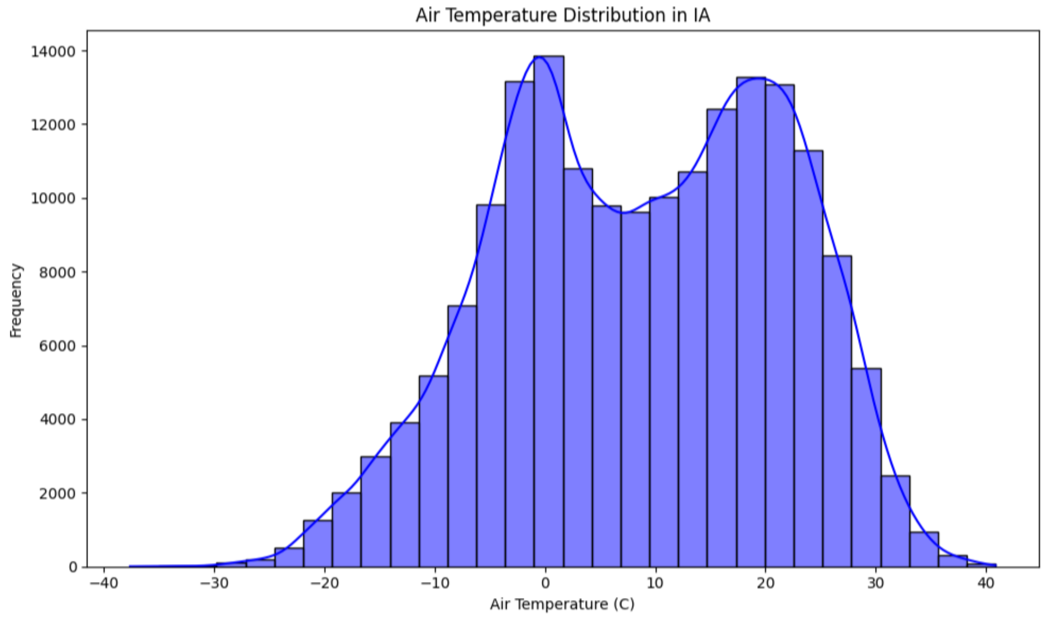


Figure 4.4 Distribution of 12 Years of Hourly Air Temperature over Iowa.

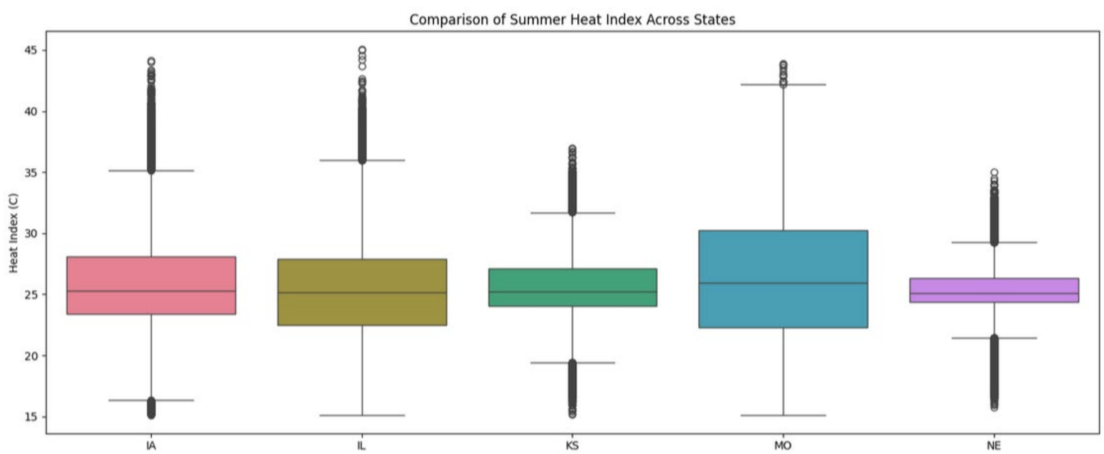


Figure 4.5 Distribution of Summertime Heat Index (combination of temperature and relative humidity) over the Five-state Area. Boxes enclose 25$^{th}$ to 75$^{th}$ percentile and whiskers extend 1.5x the interquartile range.

4.3 Measurement of Road Temperatures from Satellite Remote Sensing

In collaboration with the research group of Jun Wang at the University of Iowa, team member Sheng (Jerry) Wang explored recovery of road temperatures from satellite remote sensing using infrared bands from Landsat and ASTER. As pixel resolution is too course to resolve roads, a downscaling technique will be required, likely using machine learning to refine course spatial estimates of surface temperature to higher resolution using additional image features (likely from land use and high resolution visible imagery), with training from in situ sensor data such as the RWIS and IEM data shown in Section 4.2. This would provide observational based spatial extension of the in situ measurement network.

Samples from Landsat, ASTER, and high resolution visible imagery are shown in the figures below. Preliminary comparison indicates agreement with measured road temperatures to ±3°C (±5.4°F).

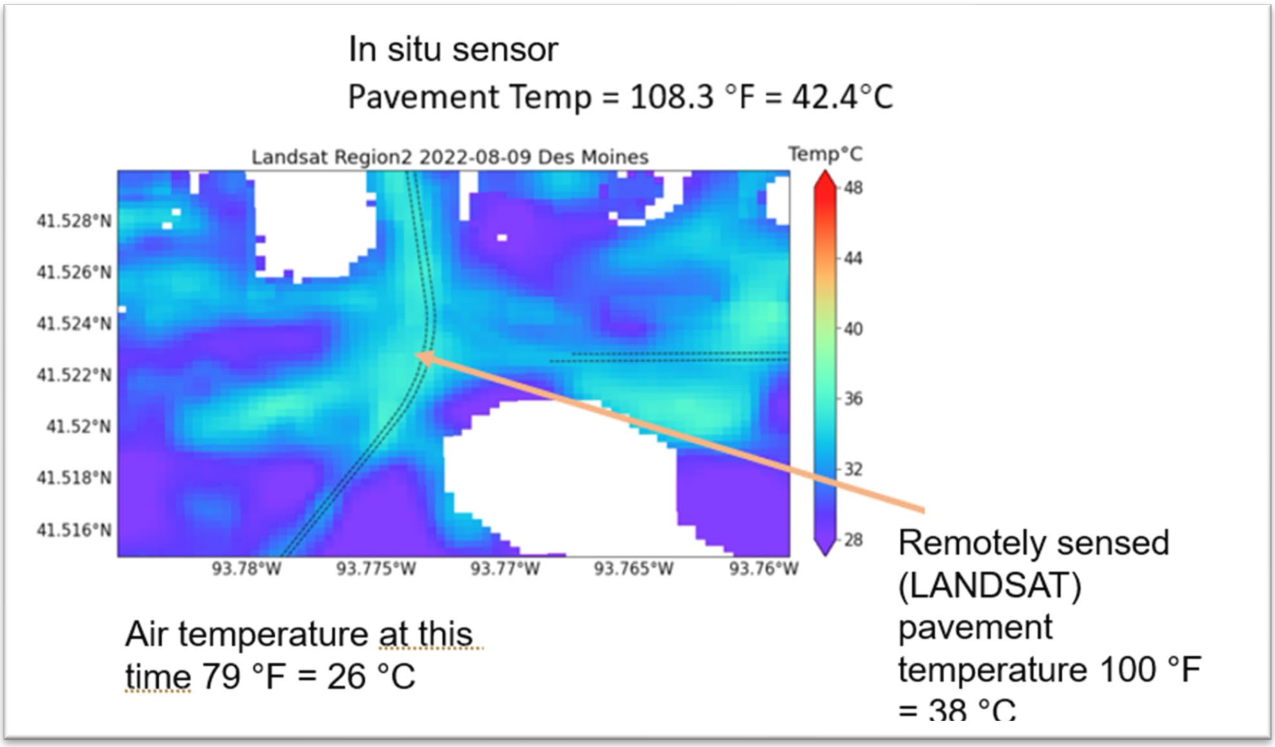


Figure 4.6 Mapped Temperature (remotely sensed from Landsat) Compared to In Situ Sensed Pavement and Air Temperature (from August 8, 2022).

ASTER data processing required exclusion of pixels with low quality flags and possible clouds. ASTER remotely sensed temperatures over Des Moines are shown below.

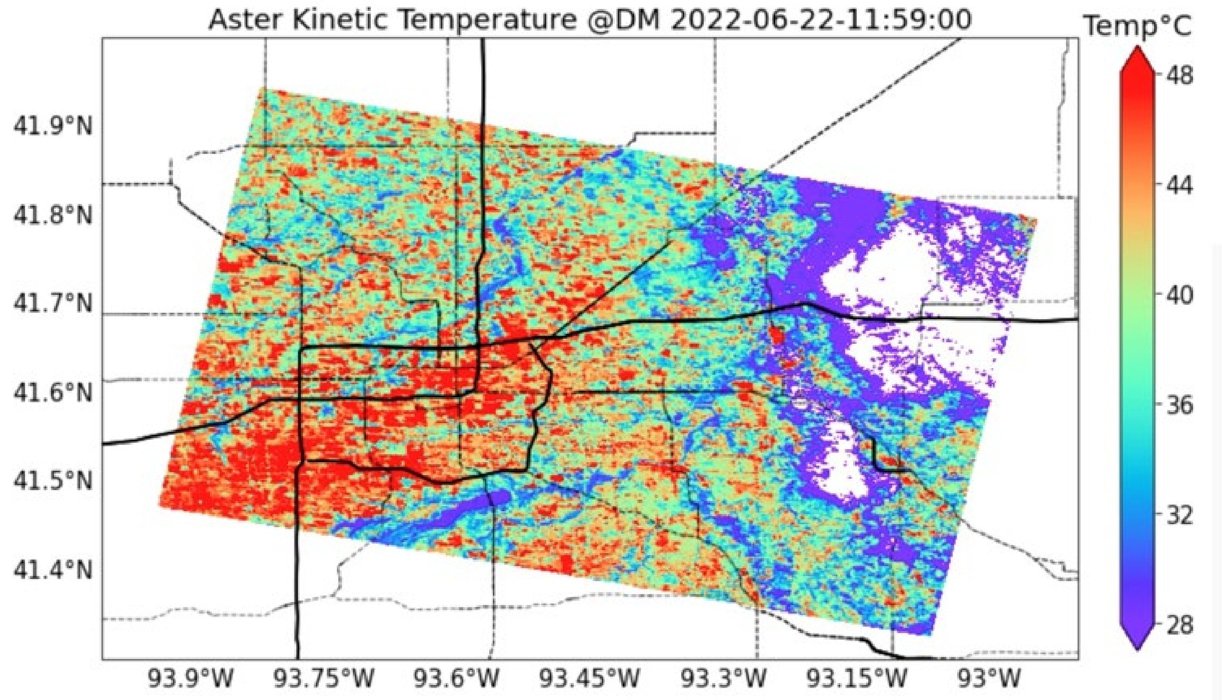


Figure 4.7 Mapped Temperature (remotely sensed from ASTER) for Jun 22, 2022

An Example of the high resolution products are shown in Figures 4.8 and 4.9. These types of datasets can be a land-cover input for machine learning models to spatially downscale results from coarser resolution products and datasets, identify pavement color of roads, and supplement other road location/information databases.

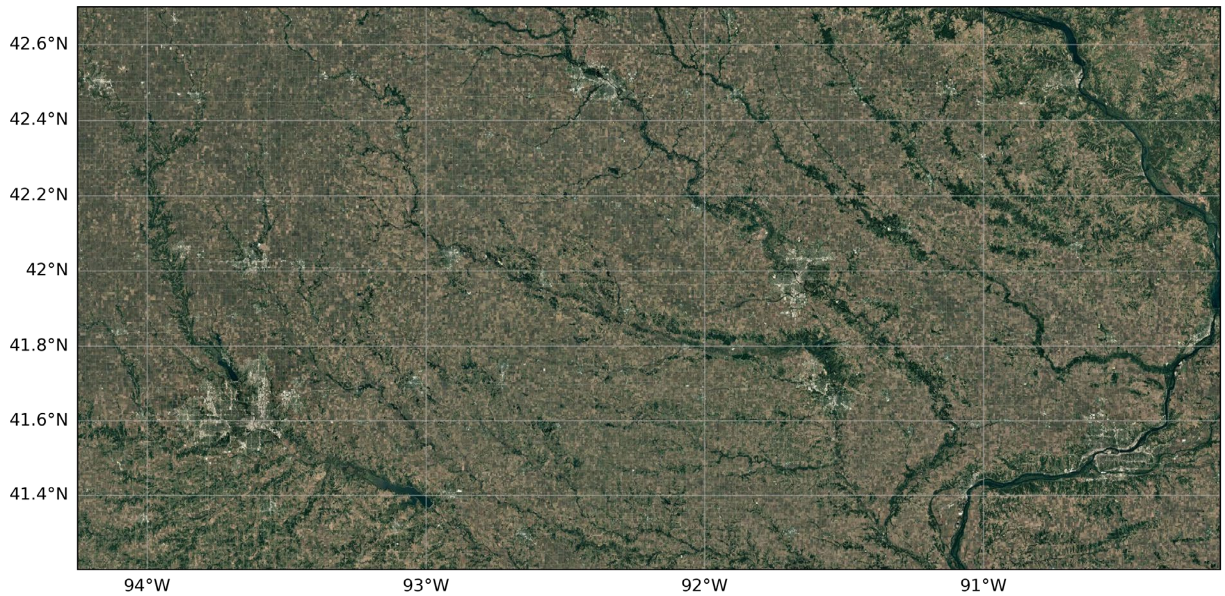


Figure 4.8 High Resolution (7.1 m pixel size) Visible Wavelength Imagery from Des Moines to the Quad Cities. (Google data downloaded and replotted by Wang).

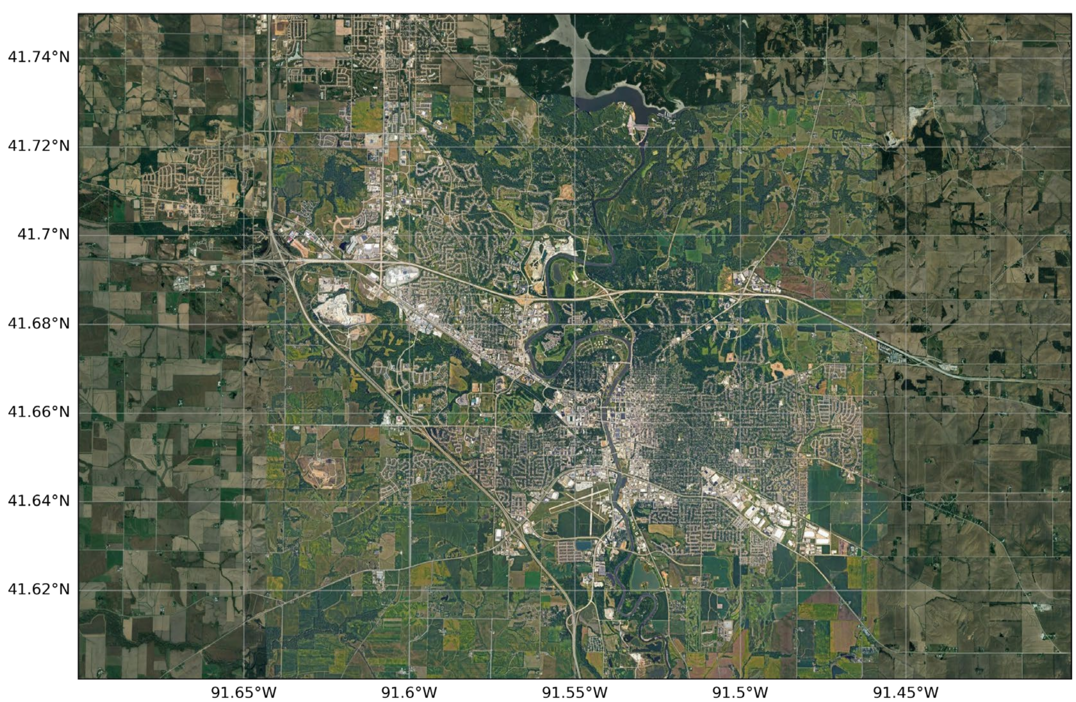


Figure 4.9 High Resolution Visible Wavelength Commercial Satellite Data over Iowa City, IA. (Google data downloaded and replotted by Wang).

# Chapter 5 Future Work

The project team intends to complete and submit a manuscript covering current and future distributions and key metrics (i.e., number of days over thresholds such as a critical heat index) at numerous weather stations and pavement measurement stations spread over the Midwest. The overall workflow for the pavement and near-road heat work is shown in Figure 5.1. This report includes the rationale and exploratory data analysis for several representative sites.

Ongoing analysis will use refined versions of the existing Python scripts that produced the figures of Chapter 4. The next steps in data analysis (not shown here) are to expand from one site in each state to multiple measurement locations in each midwestern state, and to calculate each of the metrics of Table 3.1 for each site-year combination. Spatial and temporal patterns in these metrics, and their significance relative to the impacts in Chapter 1, will be the focus of the in-preparation manuscript.

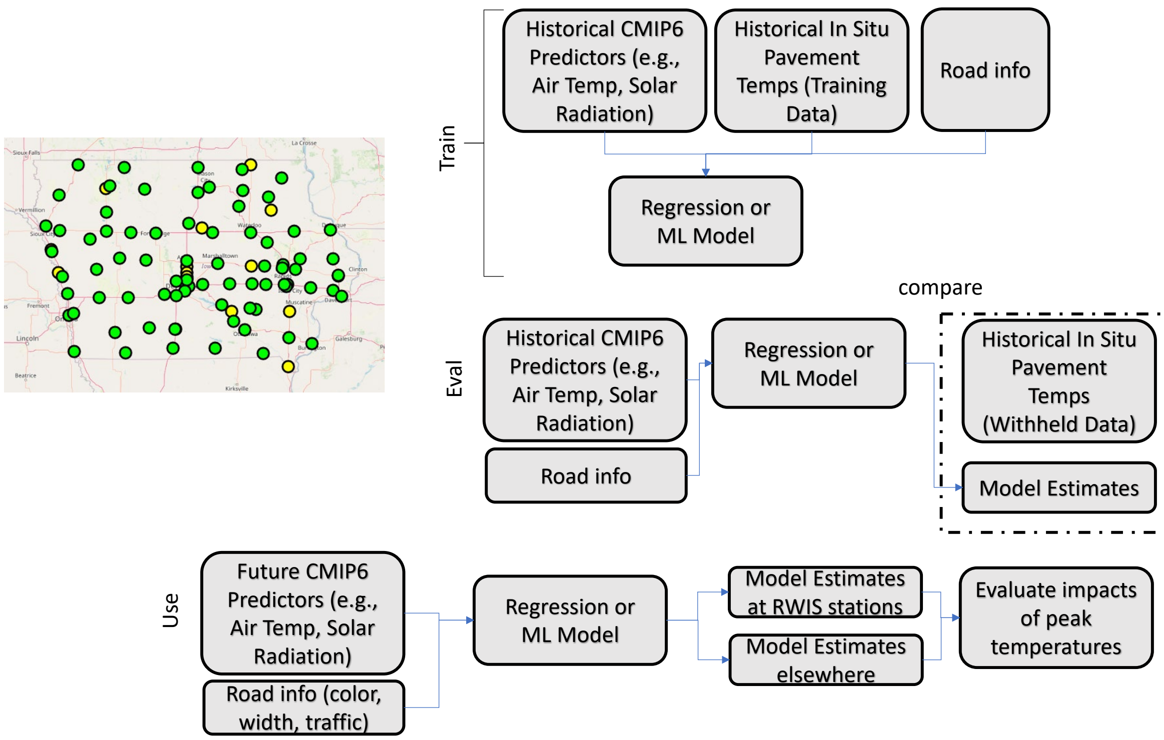


Figure 5.1 Information Flow for Temperature Models in Future Work. The map of green and yellow dots are the Iowa Roadway Information System stations (RWIS) where in situ pavement temperature is available. Abbreviations in figure include CMIP6 (Coupled Model Intercomparison Project 6, a source of future climate prediction variables) and ML (Machine Learning).

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