Effects of Tree Canopy on Rural Highway Pavement Condition, Safety, and Maintenance

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16. Abstract

An integral part of Ohio's roadscape is the canopy cover alongside and above the pavement. Roadside trees are valued for their natural beauty and because they provide shade, moderate temperature fluctuation, control evaporation, block air movement, catch rain and channel rain wash, and control local humidity. However, road managers tend to believe that trees cause accelerated moisture damage, poor density attainment, surface water pooling, and surface roughness in pavements. They infer these processes likely accelerate damage and reduce longevity of pavements, which leads to an undesirable increase in pavement maintenance and rehabilitation costs. A large body of published research confirms that trees control microclimate in urban settings, and that climatic environment is one of the factors affecting pavement deterioration. Similarly, tree canopy can negatively impact pavement surface condition, decreasing driver safety. However, these ideas are subjective to a large extent and yet to be scientifically explored through a dedicated study (especially in suburban/rural settings with seasonally cold climate such as in Ohio) of the multiple connections between trees and pavement degradation, road condition, and road safety. As a first step, this research study provides ODOT with a synthesis of existing practices from Ohio and some other states related to maintenance of roadside tree canopy (overtop and adjacent to roadways). Inconclusive evidence and conflicting information from surveys and the literature suggests an immediate need for a larger and focused study of tree canopy impacts on road pavement condition and driver safety. Consequently, this report concludes with a clear plan for designing and implementing such a study (Phase II). The most important contribution of such a detailed study will be a formal decision-making system that ODOT can use for objectively assessing the economic and environmental trade-offs of maintaining and/or cutting trees.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

NOTE: Volumes greater than 1000 L shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

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* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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- Mr. David Humphrey, P.E. - ODOT Pavements,
- Mr. Adam Au, P.E. - ODOT Pavements, and
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EXECUTIVE SUMMARY

Research Problem

An integral part of Ohio's roadscape is the canopy cover alongside and above the pavement – abundant along a significant mileage of low-to-medium-volume roads in both urban and rural areas. In addition to their intrinsic natural beauty, the roadside trees provide a wide range of benefits to the communities and drivers of Ohio including casting shade, raising real estate values, reducing the urban heat island, improving road safety, controlling stormwater runoff, supporting biological diversity, and buffering noise (Akbari et al. 1992, McPherson et al. 2005, Dumbaugh 2005). Trees absorb gaseous pollutants (Fowler et al. 1989, Nowak et al. 1998, Taha et al. 1997, 2000; Grote et al. 2016) and reduce airborne particulates (Fuzzi et al. 2015, Akbari et al. 1992, Vailshery et al. 2013). Studies of environmental psychology suggest that the presence of trees influences driver behavior and also stimulates both urban and suburban retail business (Wolf 2005). As a result, roadside trees are widely valued by the general public, and support is often expressed in public forums (Lohr et al. 2004; Wolf 2005). An innovative paper which considered the shading of suburban streets in central California (McPherson and Muchnick 2005) suggests another possible benefit from Ohio's urban and roadside trees: protection of asphalt pavement from aging and mechanical degradation. Data from research in forest microclimates, environmental effects on pavement, and urban microclimates indirectly support this view.

By contrast, anecdotal reports from road managers suggest that roadside trees negatively impact the pavement surface directly below. Tree canopy is thought to cause increases in moisture and temperature variation; and subsequently affecting the pavement's structural performance. The detrimental impacts may include; accelerated moisture damage, poor density attainment, differential rutting, and raveling. All these aspects are likely to accelerate pavement damage and reduce the pavement longevity with an undesirable increase in the maintenance and rehabilitation costs. Similarly, tree canopy alongside the roadway can affect the condition of the pavement surface raising safety concerns including; reduced skid resistance due to fallen leaves, limited direct sunlight promotes formation of black ice and fog, and branches and/or fruits falling on passing vehicles or blocking traffic lanes.

Tree canopy alongside and overtop the roadway can potentially influence the condition and safety of the pavement in a variety of positive and negative ways. However, with the exception of the research by McPherson and Muchnick (2005), observations on tree canopy and pavement condition are largely intuitive and there is very limited documentation that directly addresses the tree canopy/pavement interaction. It is unclear, for example, whether results from central California (McPherson and Muchnick 2005) apply to pavement condition in Northeastern states such as Ohio where the climate is characterized by strong seasonality with extended periods of freezing temperatures, pronounced wet and dry periods, and periods of freeze/thaw alternation.

Management practices which extend pavement surface life would potentially result in a substantial financial benefit and if roadside trees can be shown to protect pavement, as McPherson and Muchnick (2005) suggest, there is considerable potential for financial benefit for the state of Ohio. Therefore, the question of tree canopy alongside and overtop the roadway and their effects on pavement condition; and road safety appears to be ripe for exploration. This need was the basis for this research project.

Research Approach

The Ohio University research team approached the research problem by way of three key activities. These key activities are as follows:

- A critical review of all relevant transportation, civil engineering, urban and forest ecology journals and other published reports and documents. The specific purpose was to identify the following: objectives, concerns, data and analysis tools, performance measures, evaluation methodology, impacts, innovative technology used, and results; on thermal and weathering effects on asphalt pavement, safety, and on maintenance issues related to tree canopy alongside and overtop the roadway.
- Interviews and/or surveys of practitioners from ODOT district offices, specific state DOTs, and other persons from institutions/organizations that could potentially contribute to the goals of this project (e.g., Department of Forestry). The interviews/surveys aimed to solicit information on tree canopy alongside and overtop roadways with respect to policies and practices, and provide understanding of how the other state DOTs are addressing the issue of Tree Canopy as it relates to their pavement surface; and

- Preliminary investigation of a test location, preferably in close proximity to Ohio University, to make comparisons between shaded and unshaded conditions on the roadway. Specifically, observations of pavement condition, and other effects of tree canopy were observed.

Additional details of the research approach are discussed in later sections of this report.

Research Findings

The findings from Phase I of this research project on tree canopy and its effects on pavement, safety and maintenance include:

1. According to public/private groups surveyed, such as Scenic Ohio, trees are considered a valued part of Ohio communities, contributing to property values, climate moderation, retail business activity, and aesthetics, and they inspire substantial support in public meetings.
2. Transportation engineers and maintenance personnel consider roadside trees, within the right-of-way (30 feet from the centerline), a threat to driver safety; a conclusion largely based on crash data.
3. Guidance on the tree canopy management/mitigation practices is lacking. For example, there is no guidance on protection, such as pavement beside slopes/hillsides, where canopy is cutback (or trees removed) getting into protected lands. However, the pavement still remains completely shaded by the slope/hillside.
4. Pavement Condition Rating (PCR) data in a select site and anecdotal reports from surveyed DOT district personnel, suggest that roadside trees may contribute to pavement degradation.
5. A much-cited paper from California (McPherson and Muchnik 2005) suggests that urban and roadside trees protect asphalt pavement from aging and mechanical degradation by shielding them from solar radiation and moisture. This work potentially has important implications for road maintenance, an expensive and time-consuming activity, and for driver safety.
6. There are large bodies of published research on the microclimates around trees, on the response of pavement to microclimate, and on the influence of trees on urban climate, which allow the effect of roadside trees on pavement degradation and road condition to be estimated indirectly. Environmental effects, and especially climate, are one cause of pavement deterioration and failure, and trees potentially protect pavement by blocking such

effects. Those results are consistent with the conclusion that trees protect pavement and extend service life by moderating temperature fluctuation, blocking damaging solar radiation, and diverting moisture. However, an argument could also be made that trees promote degradation by delaying evaporation in the shade and reducing temperature cycles, which could be used to "heal" pavement surfaces.

7. Research on road safety confirms that trees function as immovable obstacles in many crashes, particularly beside rural roads. However, there is countering evidence that roadside trees, particularly in urban/suburban areas have a traffic-calming effect.
8. There is a clear contradiction between the surveyed transportation engineers' experience and conclusions based on the bulk of published research. However, published work has not directly addressed the connection between trees and pavement degradation, road condition, and road safety. The California study has not been tested by later research, and results from dry, warm, seasonally stable climates cannot be directly applied to a seasonally wet and cold climate such as Ohio.
9. Transportation engineers, maintenance personnel, and interested public/private groups surveyed, claim the topic of tree canopy and its effects on the pavement, safety, and maintenance comes up in their discussions and were interested in the findings of any research that could present any definitive answers.

Recommendations and Benefits

Based on the findings of this research project, it is recommended that the Ohio Department of Transportation (ODOT) develop a decision making tool or process that will assist ODOT Districts with their tree canopy maintenance. This decision making tool should be based on focused research to assess the impact of trees and tree species on pavement degradation, road condition, and road safety in climatic conditions typical of Ohio. Such a tool would bear a resemblance to Figure 1.

The potential financial and safety benefits provide a strong incentive for such research. To test the possible mechanisms of tree-pavement interaction and to gauge their relative magnitude, pavement performance needs to be examined in the context of real road environment. To establish the strength of tree effects, they must be judged against realistic background variation in pavement condition by use of extensive replication. Paired comparisons are highly recommended to control for background variation in traffic loading, road structure, urban geometry, and pavement age.

Another recommendation would be to assess whether the current PCR system is adequately reporting damage due to tree canopies.

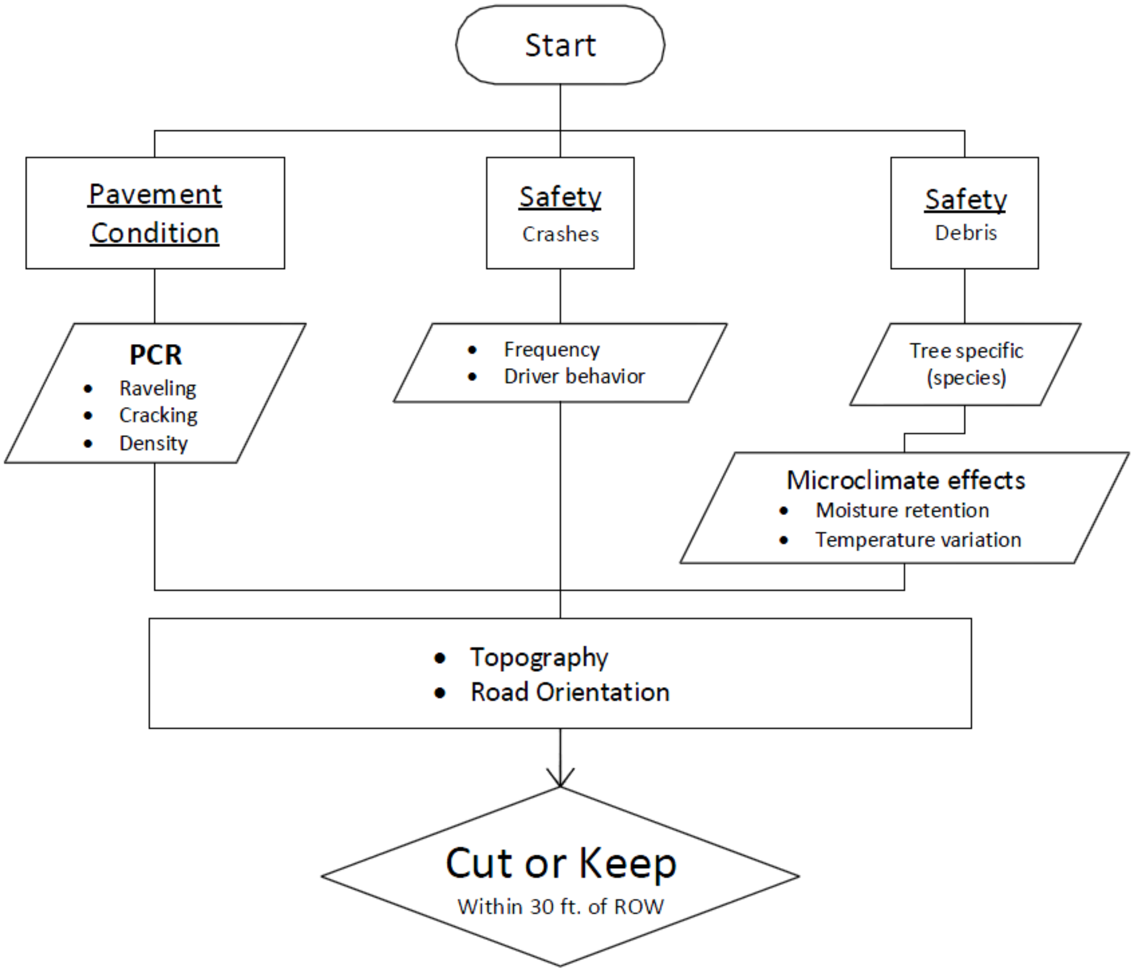


Figure 1. Decision Making Process for Tree Canopy Maintenance.

RESEARCH CONTEXT

Background

Trees are an integral part of the Ohio roadscape, abundant along a significant mileage of low- to medium-volume roads in both urban and rural areas. Roadside trees tend to be deciduous species (those that lose their leaves in the winter), native to the Central Hardwoods forest type, or common transplants from the moist-temperate zones of western Europe or eastern Asia (Zanon 2014). In addition to their intrinsic natural beauty, trees provide a wide range of benefits to the communities and drivers of Ohio including casting shade, raising real estate values, reducing the urban heat island, improving road safety, controlling stormwater runoff, supporting biological diversity, and buffering noise (Akbari et al. 1992, McPherson et al. 2005, Dumbaugh 2005). Trees absorb gaseous pollutants (Fowler et al. 1989, Nowak et al. 1998, Taha et al. 1997, 2000; Grote et al. 2016) and reduce airborne particulates (Fuzzi et al. 2015, Akbari et al. 1992, Vailshery et al. 2013). Studies of environmental psychology suggest that the presence of trees stimulates both urban and suburban retail business (Wolf 2005). As a result, roadside trees are widely valued by the general public, and support is often expressed in public forums (Lohr et al. 2004; Wolf 2005).

An innovative paper which considered the shading of suburban streets in central California (McPherson and Muchnick 2005) suggests another possible benefit from Ohio's urban and roadside trees: protection of asphalt pavement from aging and mechanical degradation. McPherson and Muchnick (2005) compared the rate and extent of pavement degradation under tree canopies with pavement condition under the open sky. They reported that a dense street-tree canopy significantly reduced thermal cracking in the pavement below the canopy, leading to an estimated 58% reduction in maintenance costs over 30 years.

The basic physical processes described in McPherson and Muchnick (2005) apply to roads throughout America, so it is reasonable to expect similar pavement protection in other regions as well. In the average US city approximately 23% of street pavement is shaded by trees. A range of 1.8 - 27.6% shading was reported in a survey of Western cities (McPherson et al. 2005), and the proportion is probably higher in many older neighborhoods and rural areas, (GRM, personal observation). If the benefit observed in California can be generalized, these observations suggest enormous potential savings in maintenance costs nationwide.

Considering the potential benefits, it seems reasonable that McPherson and Muchnick's (2005) preliminary study would quickly be followed up to confirm the findings and to explore regional variation in tree/pavement effects. However, we can find no similar studies; an intensive search of science and engineering databases suggests that no other work has been done on the topic of trees and pavement condition. The California study has been cited extensively in public outreach materials (e.g. Devens Enterprise Commission, accessed 11/12/16), but has only been cited seventeen times in the science and engineering literature (Web of Science, accessed 11/12/16). All of the citing papers mention the study as part of a general overview of urban forestry, but none present original data on pavement condition or address the tree/pavement interaction directly. The authors themselves do not know of any follow-up work (Greg McPherson, personal communication).

The question of tree effects on pavement condition and road safety appears to be ripe for exploration. It is unclear, for example, whether results from central California applies to pavement condition in Northeastern states such as Ohio. The Ohio climate is characterized by strong seasonality with extended periods of freezing temperatures, pronounced wet and dry periods, and periods of freeze/thaw alternation (Midwestern Regional Climate Center, accessed 11/12/16), none of which occur in the warm, dry, seasonally stable location of the original study. The tree - pavement interaction is likely to be more complex in Ohio than in California, and needs to be explored specifically within our region. This need was the basis for the ODOT RFP 2017-5.

Pavement in Ohio

The road surface is a vital component of our surface transportation system. Roads are the principal arteries connecting communities in Ohio today, allowing the flexible movement of people and goods between residences, commercial locations, and public facilities. State and local economies are completely dependent on the good condition of their road networks. For example, 68% of Ohio's freight is moved in trucks that operate on public roads (Parsons Brinckerhoff, 2013). It would be impossible to imagine a modern economy in the State of Ohio if its road network was not in top condition, making maintenance of the road network one of the highest economic priorities.

Non-Interstate roads, which have the greatest potential for shading by tree canopy alongside and overtop, make up the largest portion of the total pavement length in the US (minor collectors and local roads account for 77% of rural and 72% of urban pavement length; US DOT, 2015). They form an essential part of the national road network, distributing traffic to individual destinations (businesses, government offices, as well as ordinary residences). Within the state of Ohio there are approximately 49,419 lane-miles of paved highway (not including the turnpike), of which 22,763 lane-miles of small rural roads (minor arterial, major collector, and minor collector) are the responsibility of ODOT (ODOT 2016). Many of these rural miles are tree-shaded, particularly in District 10.

Pavement in rural roads is most likely to be affected by adjacent trees, as these roadways are relatively narrow, have narrow shoulders, and are most closely flanked by trees. In urban areas several million dollars are spent on routine pavement maintenance annually (ODOT 2011), equivalent to ca. $481/lane-mile/year. We are not aware of similar data for rural areas, but one can safely assume that expenditures on rural roads are also high. Thus, management practices which extend pavement surface life would potentially result in a substantial financial benefit at all levels of government. If roadside trees can be shown to protect pavement, as McPherson and Muchnick (2005) suggest, there is considerable potential for financial benefit for the state of Ohio.

Research Objectives and Tasks

The overall goal of this research was to provide ODOT with a synthesis of practice on the concept of tree canopy (overtop and in close proximity) to the roadway. In particular, to seek a better understanding on the influences that tree canopy has on pavement integrity, drivable surface condition, safety, and any maintenance practices available. This research also sought to acquire insights on the concept of tree canopy as understood by other state DOTs. The specific objectives of this phase of the research study were as follows:

1) Conduct a review and synthesis of current published research and management practices on tree canopy as it relates primarily to pavement condition, safety and maintenance;

2) Investigate and gain a thorough understanding of the concerns and current practices that ODOT have with regard to interactions between tree canopy and pavement surface;
3) Interview practitioners from other state DOTs to investigate their current practice and guidance;
4) Conduct preliminary evaluations on a trial site(s) to determine the effects of canopy; and
5) Based on findings from the items above, develop a detailed field monitoring plan for Phase II of the project.

To accomplish the research objectives, the research team from Ohio University completed the following tasks:

- Task 1: Review of existing literature on tree canopy overtop and alongside the roadway;
- Task 2: Investigate the current views and practices within Ohio regarding tree canopy overtop and alongside roadways;
- Task 3: Develop protocol for practitioner interviews;
- Task 4: Interview practitioners within select ODOT district offices and also within select state Departments of Transportation;
- Task 5: Perform “Test of Concept” analysis;
- Task 6: Develop recommendations and detailed field monitoring plan for Phase II; and
- Task 7: Develop final report on Phase I.

RESEARCH APPROACH

The research approach for this project consisted of three main elements: a comprehensive literature review, interviews and/or surveys of practitioners, and a preliminary investigation on tree canopy. In depth detail of each component of the research approach for this project are discussed in this section.

Literature Review

The question of how roadside trees influence pavement condition and road safety requires an understanding of several distinct topics including environmental effects on asphalt pavement, the microclimate created by trees, the effect of microclimate on road safety, and the role of trees in urban ecosystems. Our approach is to review each of these subject areas in turn, looking for areas of overlap. This literature review is targeted to shed light on the possibility of tree/pavement interaction. Specifically, the review addresses three fundamental questions:

1. In what specific ways do trees alter the microclimate nearby and is it possible to generalize about numerical ranges of such alteration?
2. Do the forms of environmental alteration created by trees have the potential to improve or degrade pavement performance or accelerate the wear and aging processes?
3. Do the zones of environmental alteration around trees affect the traction, visual perception, traffic speed, and stopping potential of cars on the road?

The purpose is to identify critical questions that need to be addressed in future research. The literature search tried to discover studies from moist-temperate climates similar to Ohio, and studies which use deciduous tree species similar to those encountered in Ohio. This review explicitly seeks studies that make direct comparisons of tree-covered and adjacent uncovered sites. However, little has been published on tree microclimate and environmental pavement effects in Ohio, and methodology varies considerably; necessarily examples are used from all over the world. It should be noted that research has also been directed to tree roots damaging sidewalk pavements (Sydnor et al., 2000; D'Amato et al., 2002). The effect of tree roots is a separate topic, and will not be addressed here.

Trees Shape Their Environment

Trees control the physical environment under their leafy canopies in several ways which are potentially relevant to pavement condition. Most obviously, trees block sunlight and create shade at ground level. The energy balance of the earth's surface can be described in terms of the absorption and dissipation of solar energy (Geiger, Aron, and Todhunter 2009). Incoming solar radiation is received in the form of visible and ultraviolet light (ca. 0.2-5 µm wavelength) whereas outgoing radiation is in the form of heat (ca. 5-40 µm). During the day, surface temperature is dominated by incoming radiation as energy input exceeds energy loss by re-radiation from the ground. The surplus energy is either absorbed into the ground, re-radiated to the air, evaporates moisture, or melts ice. The net radiation balance at night, in the absence of solar input, is dominated by outgoing radiation to the sky in the form of heat.

Trees and radiation

If plants are present, the uppermost layer of leaves becomes the thermodynamically active surface reflecting, absorbing, and transmitting portions of the incoming solar radiation. For example, the upper canopy of a beech/oak forest in south-central Germany absorbed energy during the day, reaching a temperature of 27°C (81°F), while the air just above the forest floor remained a relatively cool 18°C (64°F) (Geiger and Amann 1931). At night, the vertical temperature gradient disappeared, and air at all heights was 18°C (64°F). The forest canopy as a whole typically absorbs or reflects 75-90% of incoming radiation (McCaughy 1987; Shuttleworth 1989). The initial scattering of solar radiation is controlled by the irregular surface of the leafy canopy (Baumgartner 1956). In deciduous species with spreading canopies (including most roadside tree species in Ohio), most light is absorbed or reflected by the top-most 1-2 layers of leaves. The relative absorption of subsequent layers declines as one moves down the tree. Only 1-3% of above-canopy radiation may penetrate to half the height of a young beech or pine tree (Geiger et al. 2009).

Transmission through the canopy is controlled by canopy density (leaf layers per unit area, expressed as ‘Leaf Area Index’), leaf spectral properties, solar elevation, tree height, and the size, shape, and orientation of individual leaves (Oke 1987, Breman and Kessler 1995, Lieffers et al., 1999; Parisi et al., 2001). Transmission through the canopy to the ground varies between tree species and growth forms. For example, a deciduous forest has a Leaf Area Index of approximately 5.3 whereas conifer forests can be as high as 7.0 (Asner et al. 2003). Saplings (small trees 10-20 years old) have a greater leaf density and greater light absorbing capacity than younger and older trees (Mitschrlich 1940).

The amount of light penetrating to the forest floor varies between ecosystems: in tropical rainforests as little as 0.4-1.0% of outside light reaches the forest floor (several references in Geiger et al. 2009). In contrast, Acacia species in a sub-Saharan savanna were measured to transmit as much as 35-55% (Belsky et al. 1989). In the Central Hardwood Forest of the eastern U.S. light at the forest floor may be as little as 1-5% of radiation falling on the crown canopy (Hutchinson and Mott, 1977; Matlack, 1993), and may have a much different spectral signature (Larcher, 2003). Individual tree species range from approximately 70-89% solar attenuation in Campinas, tropical Brazil (Abreu-Harbich et al. 2015). Trees species differ in the proportion of light penetrating the canopy (e.g. Heisler 1986) apparently reflecting tree architecture and leaf form.

The ability of solar radiation to warm the ground surface under a tree depends on transmission of light through the canopy. During the day, low light levels under a tree canopy lead to low ground temperatures relative to open areas. At night, downward reflectance by canopy foliage reduces energy loss by re-radiation from the ground leading to higher temperatures under the canopy (Geiger et al., 2009). Soil 3 cm under grass exposed to direct sunlight warmed as much as 13°C on an August day in eastern England (Oliver et al. 1987), and an increase of 2°C was even detectable 30 cm below the ground surface. In contrast, soil under a dense forest nearby only increased 3°C at 3 cm (0.4 in) depth, and was not detectable at 30 cm (12 in). Some of the contrast can be attributed to transpiration and conversion to latent heat in the forest, but most appears to be due to absorption of radiation by the tree canopy. *Acacia* trees in Kenya reduced solar irradiance by 45-65%, leading to a 5-11°C decline in soil temperature under their canopies relative to nearby open areas (Belsky et al. 1989). Thus, the ground under trees experiences less extreme thermal cycling in summer and less frequent freezing in winter (Nunez and Bowman, 1986).

Even leafless trees can block a significant portion of solar radiation; leafless *Acer* and *Platanus* species absorbed 30-40% of incident radiation in a study in central Pennsylvania (Heisler 1986). Leafless *Faidherbia albida* reduced incident radiation by ca. 50% in western Niger (van den Beldt and Williams 1992; and see examples in Boffa 1999). Thus, thermal effects can also occur in winter, when trees have shed their leaves.

Moisture below tree canopies

Shading can also affect air humidity and ground-surface moisture under tree canopies. At night, because long-wave radiation is controlled by the tree canopy, the ground under the tree remains warmer than ground which is radiating directly to the sky. Warm ground under a tree canopy in east-central Germany was less likely to be moistened by dew than cooler ground under an open sky (4-5% as likely as ground under open sky; Made 1956) leading to a drier ground surface. Conversely in daytime, cooler air and a higher vapor pressure are maintained in the trunk space (the air below the canopy) than in the canopy itself or in nearby open areas (Geiger et al. 2009). Thus, any dew that has appeared evaporates more slowly in the shade of the canopy than it does under an open sky (Geiger, Aron, and Todhunter 2009) leading to a moister ground surface. Similarly, rainfall may evaporate more slowly under canopies than in open areas. In a study of forest edge microclimate in southeastern Pennsylvania, lower temperatures under trees led to higher humidity (i.e. lower vapor pressure deficits), less evaporation than in adjacent open areas, and greater moisture in the litter layer (Matlack, 1993). Surface wetting may translate into greater soil moisture beneath tree canopies. Generally, soil is 4-53% moister under tree canopies than in open areas in sub-Saharan Africa notwithstanding the absorption by tree roots and decreased evaporation (Boffa 1999).

Tree canopies have an enormous capacity to catch and hold rainfall, reducing wetting under them by as much as 50% relative to adjacent open areas (Linskens 1952; Belsky et al. 1989). A 20-40% reduction of rainfall is more typical of deciduous tree species such as we have in Ohio, with greater absorbing capacity in larger trees and those with denser foliage (Llorens and Domingo, 2007; Zimmerman et al., 2007). Canopy storage can vary enormously depending on the species, size, and foliage density of a particular tree. In general, more rainfall is intercepted in older than younger forest stands (Geiger, Amon, Todhunter 2009). Calder et al. (1986)

reported 21% interception of rainfall in secondary rainforest in West Java. Vis (1986) reported 11-25% retention at four rainforest sites in Columbia, with the amount retained in the foliage depending on the species of the tree, reflected in its size and branching structure.

In semi-arid savanna of southeastern Arizona, the amount retained by *Quercus emoryi* was proportional to the size of individual trees (Haworth and MacPherson 1995). Expressed in terms of rainfall, canopy storage capacity typically ranges from 1-3 mm of arriving rain (Shuttleworth 1989, Geiger, Amon, Todhunter 2009) but retention of 12-18 mm has been observed in stands of mature conifer species (Delfs 1955). Intercepted water may be a) retained on leaves (a form of temporary storage), b) drip through the canopy (through-fall), or c) flow down the stem (stem-flow), channeling the water to the base of the tree. Hardwoods typically intercept 10-20% of water that falls on them, whereas conifers intercept 20-40% (Zinke 1967). Stemflow may account for 0.6-27% (Xiao et al. 2000).

A Bradford pear was measured as intercepting 23% of precipitation without leaves (Xiao et al. 2000), indicating that deciduous trees can provide some benefit even in the winter. In the same rain events a cork oak intercepted as much as 42% of precipitation. Tree canopies can become saturated; the cork oak began stem flow and through fall after 60 minutes of precipitation. Crown storage was estimated as 1.0 mm for the pear and 2.0 mm for the oak, with the difference attributed to the rougher bark and denser canopy of the oak (Xiao et al. 2000). Thus, species differ in their rainfall interception capacity.

Xiao and McPherson (2002) estimated that trees in Santa Monica, California, cumulatively held 6.6 m^3 of water per tree annually (ca. 27.3% of incident rainfall) providing temporary storage of runoff water and maintaining a drier pavement underneath. Species differed in their capacity for holding water, reflecting branching angles, bark texture, and leaf density. Storage was greatest in short-moderate rain events; trees became saturated in storms, allowing large amounts of through-fall. Depending on the length and intensity of rainfall, retention ranged from 6-93% in woodlands of southeastern England (Ovington 1954). Thus, wetting under a tree canopy by both dew and rain depends on both canopy density and the amount of moisture. In a season of light dew or brief showers, a substantial amount of moisture could be prevented from reaching the pavement surface.

Trees may also collect snow, creating a local zone of shallow snow depth beneath the canopy. Snow is an insulator, protecting the ground from extremely low temperatures (Jean and Payette 2014). Conifer trees measured near Fairbanks, Alaska, collected substantial amounts of snow in their canopies, leading to temperatures 7-15°C lower at their bases than in undisturbed snow nearby (Sturm 1992). Deciduous trees, by contrast, had more snow at their bases than in open areas. In Arctic conditions, ice lenses form under individual trees, possibly due to the reduced snow layers (Viereck 1965). To the extent that trees block snow, they may increase the duration and thickness of frozen soil.

The literature on microclimate demonstrates that trees control the energy budget of the ground beneath them and substantially affect the accumulation and persistence of moisture, factors known to be relevant to pavement condition. Variation in air and ground temperature, humidity, and ground moisture under the canopy is dependent on species identity (reflected in canopy architecture) and the size and structure of individual trees. The range of variation described here is easily noticeable to humans, and potentially sufficient to affect the properties of asphalt pavement.

Environmental Effects on Asphalt Pavement

The most common road surface used in the U.S. is asphalt concrete, comprising 95% of total lane length (Federal Highway Administration 2015). Asphalt is virtually the only pavement material used on rural roads in Ohio, (covering 99.8% of lane length; FHA 2015). Asphalt pavement is constructed of layers of varying density and tensile strength. The overall road structure and the composition of individual layers are fine-tuned to carry an expected weight of vehicles during a clearly defined design life. To ensure a safe, comfortable driving surface this structure must be continually maintained. However, even optimally designed and maintained pavement is subject to aging and gradual deterioration.

Longevity is strongly influenced by the environmental conditions of a particular road section. The environment acts on pavement through a variety of mechanical and chemical processes, some of which are potentially influenced by overhanging trees. An overarching tree canopy is potentially beneficial to pavement performance because it blocks damaging radiation, buffers variation in temperature, and protects pavement from moisture, a view supported by many of the observations of tree microclimate described above. Alternatively, a tree canopy may be detrimental to the extent that it increases variation in temperature and moisture, an interpretation which is also consistent with the tree microclimate literature. It is also possible that tree-caused environmental effects, although present, are minor compared to other factors acting on pavement condition. To choose between these interpretations it is necessary to understand the structure and properties of asphalt at a basic physical and chemical level.

Pavement layers are designed to resist wear and distribute the traffic load to base layers and the ground beneath (Adlinge and Gupta 2010). The top layer (the surface course) is designed to withstand abrasion and weather. Wheel loading is most concentrated at the surface, requiring the greatest tensile strength in the surface course (Jung and Vinson 1994). Strength and abrasion resistance is provided by a mixture of petroleum-derived asphalt binder and a mineral aggregate. Typically, asphalt concrete contains approximately 7% asphalt binder by weight; the remainder is crushed stone or gravel. Lower tensile strength is acceptable in the second and subsequent layers (the base course, subbase, and soil, respectively) which are designed to spread a more diffuse traffic load over progressively larger areas (Cool California 2016).

The asphalt binder is a mix of high-molecular-weight organic compounds held together by fairly weak Vander Waals forces (Little and Jones 2003). Binder adheres to the mineral aggregate due to the uneven distribution of charge in both (neither asphalt nor aggregate are composed of polar molecules). Physical properties of the pavement mix are determined by the proportions of high- and low-molecular-weight compounds in the binder material (Asphalt Restoration Technology Systems 2016) including saturated hydrocarbons, naphthene aromatics (maltenes), polan aromatics, and asphaltenes. Analytically it is useful to treat this mixture as a colloidal suspension in which asphaltenes (phenolic and hetrocyclic) behave as fibrous inclusions, and maltenes provide a tacky, glue-like matrix (Quddus 1992). In practice, however, it is usually not possible to separate the large number of high-molecular-weight compounds. The mixture of organic compounds determines the visco-elastic properties of the asphalt binder, allowing the pavement mix to resist tensile stresses created by traffic loading and thermal expansion and contraction (Alavi et al. 2015). Elasticity is related to temperature; asphalt becomes soft as temperature rises, a property which allows easy road construction but which may also aggravate pavement deterioration (Quiao et al. 2013).

Degradation is caused by climatic conditions (sunlight, temperature variation, water penetration) and traffic loading (primarily heavy trucks), or through an interaction of climate and loading effects (Croney and Croney 1998). The average service life of asphalt pavements ranges from approximately nine years in regions with wet climates and freezing winter temperatures to 20–40 years in dry regions, a generalization which holds across Asphalt Institute traffic classes I – IV (Boyer et al., 1999). After approximately 40 years expensive replacement is necessary. New highways in Britain are designed for a service life of approximately 40 years, with replacement of the surface course every 10-15 years (Willway et al. 2008). Because local streets, rural roads, and small collectors generally experience less truck traffic than inter-urban highways, we can expect a greater importance of climatic factors in the deterioration of urban and secondary roads. A study in nearby Indiana estimates that 74% of the cost of pavement deterioration is caused by environmental factors relative to only 26% caused by traffic loading (Zongzhi et al., 2002).

Pavement temperature

Asphalt pavement has a substantial capacity for absorbing solar radiation under an open sky. The surface course may absorb 80-95% of the energy in direct sunlight and reach temperatures as high as 67°C (150°F; Scott et al. 1999; US EPA 2008). The degree of solar heating of pavement is based on properties of the pavement material and its immediate environment including the specific heat capacity of the paving material, the thermal conductivity of the material (the ability of heat to flow away from the heated zone), the surface albedo (the reflectivity of the paving material, resisting solar heating), the geometry of the urban environment (controlling humidity and the duration and intensity of solar input), and heat generated by traffic using the pavement (Bowler et al. 2010).

Thermophysical models suggest that albedo (reflectivity) is the most important factor controlling pavement temperature under an open sky (Gui et al. 2007) and this high ranking is borne out by empirical observation: In a comparison of pavement types in Berkeley, California, each 10% increase in albedo led to approximately a 10°C drop in pavement temperature (Akbari et al. 2001). Asphalt has a relatively low albedo (reflective capacity) compared to soil and

Portland cement pavement (Oke et al. 1989). In Phoenix, Arizona, Portland cement pavement was consistently 0-10^{o}C cooler than asphalt pavement because the former has a higher albedo, reflecting more of the incoming solar radiation (Golden et al. 2007). Absorption of solar energy declines with pavement age and traffic abrasion, which tend to increase albedo; after seven years, absorption may be reduced to 80% making the pavement proportionally cooler (Tran et al. 2009).

High temperatures soften the mastic binder potentially leading to rutting, shoving, and bleeding (exudation of binder) with traffic loading on a scale of months or years (Willway et al. 2008). As the climate warms, we may expect more of these forms of degradation (Dawson 2014). Conversely, cool pavement resists softening and deformation under traffic loading, and, so, lasts longer (Cominsky et al. 1994). Modeling heating effects in the Los Angeles basin Akbari et al. (2001) predicted that a 10°C decrease in pavement temperature could lead to a 25-fold increase in longevity. Extreme cold may cause contraction in pavement volume, increasing tensile stress and potentially causing transverse cracking. Tensile cracking occurs at very low temperatures (approximately -30°C) in fresh asphalt, but appears at progressively warmer temperatures as asphalt ages (Alavi et al. 2015).

On a daily time scale, solar heating drives a diurnal cycle of expansion and contraction which can lead to "fatigue" cracking analogous to fatigue failure in metals (Timm and Voller, 2003; Alavi et al. 2015). Paving materials differ in their capacity to transfer and store radiant heat, controlling their potential for thermal expansion (Kevern et al. 2012). In general, the amplitude of diurnal temperature cycling increases as the thermal conductivity of the asphalt concrete mixture decreases (Shi et al. 2015). In Saitama, central Japan, Asaeda and Ca (1993) compared diurnal heat cycling in a variety of paving materials, and confirmed their observations with thermal exchange models. They reported that asphalt pavement increased in temperature more than soil or cement due to its low albedo, and conducted heat away from the surface more slowly. Thus, there was a stronger vertical gradient of temperature in asphalt than in the other substrates, and a more extreme diurnal fluctuation at the surface.

These thermal properties appear to make asphalt pavement particularly vulnerable to fatigue cracking, which would be visible as transverse cracking in response to expansion and contraction along the road axis. Thermal expansion and contraction can generate tensional stresses of 0.1–0.6 MPa between 0-15°C – a range typical of spring and fall cycling in many temperate-zone climates (Tabatabaee et al. 2012). Fatigue cracking begins in the surface course and progresses downward under the weight of traffic (DeBeer, Fisher, and Jooste 1997; Read and Whiteoak, Shell Bitumen Handbook 2003).

Thermal cycling aggravated by traffic loading causes many of the familiar patterns of cracking observed in asphalt pavement (e.g. alligator, longitudinal, transverse, block, reflective, and edge cracking) (Asphalt Institute 2009). Using data from Minnesota, Washington, and Virginia, Quiao et al. (2013) applied sensitivity analysis to judge the relative importance of temperature, precipitation, wind speed, percent sunshine, groundwater level, and temperature variation on four forms of pavement deterioration. In each case, temperature and temperature variation were most influential, potentially increasing longitudinal cracking, transverse fatigue cracking, and AC rutting. In the Virginia trial, as little as 5% increase in temperature decreased the service life of asphalt pavement by more than 20%.

Aging of pavement

The chemical and physical properties of asphalt pavement change through time in a process that can be described as “aging”. Pavement aging actually involves two chemical processes: oxidation of high-molecular-weight compounds and volatilization of low-weight compounds (Somayii 2001). Oxidation caused by ultraviolet light entails breaking of long-chain molecules which reduces the viscous resilience of the mastic and leads to a brittle pavement matrix. Higher values of Young's modulus (pavement stiffness) are observed as pavement ages (Dawson 2012) resulting in a gradual loss of flexibility over 5-10 years (Bell, 1989; Khalid, 2002). Maltenes and saturated hydrocarbons break down leading to a visible greying of the pavement surface (Asphalt Restoration Technology Systems 2016). Fuel and oil droplets from traffic contribute to this process.

Volatilization of low-molecular-weight oils and resins leads to a shrinkage in pavement volume, which may produce transverse cracking (Asphalt Institute 2009). As low- molecular-weight compounds are lost there is a proportional increase in high molecular weights, increasing stiffness of the binder. For example, long-established road sites near Clemson, South Carolina, showed a 15-40% increase in high-molecular-weight compounds relative to new pavement (Lee et al. 2008). Polar compounds (carbonyls) accumulate within the binder reducing its fracture stress threshold, leading to cracking, and increasing its viscous softening stress (Alavi et al. 2015). Age hardening is more rapid at high temperatures (Ishai 1987; Willway et al. 2008). The rate has been observed to double for every 10°C rise in temperature. High ambient temperatures contribute to oxidation and aging, but solar radiation appears to play the dominant role (Milani and Takallou 2009; Dawson 2014).

Loss of flexibility by oxidation or volatilization can result in failure of the binder under tire abrasion, causing "raveling" of the pavement surface (ODOT, 2004). Aged pavement is particularly vulnerable to thermal fatigue cracking. Fatigue cracking, especially transverse cracking, often appears to be an interaction effect caused by the loss of flexibility due to age, thermal cycling, and a large number of load cycles (Quiao et al. 2013). In a city-wide survey in Irbid, Jordan, computer-sensed pavement condition was regressed on several measures of wear and location in a GIS environment (Obaidat and Al-Kheder 2006). Traffic loading and pavement age appeared as the most important driving factors, showing R^2 values between 0.426 and 0.965 - very high levels of predictive power.

Water in pavement

Moisture influences the structure and properties of asphalt-based concrete in several ways which potentially accelerate pavement degradation. Water may penetrate natural pores in the pavement matrix (asphalt concrete is naturally 8% porous), or may find its way into microcracks formed by thermal cycling (Si et al. 2014). Water may also be suspended within the binder material (spontaneous emulsification; Little and Jones 2003). Because shading by tree foliage is known to control condensation, evaporation, and rain wetting at ground level, it is possible that roadside trees can reduce forms of pavement deterioration mediated by moisture. Unfortunately, the small number of studies on shading and pavement condition have been limited to dry, subtropical climates (McPherson and Muchnik, 2005; Mascaro, 2012); little is known about the link between shading and moisture- or freeze-mediated pavement damage.

The severity of most forms of pavement damage is greater with water present (Stidger, 2002). Pavement stiffness, for example, can be dramatically reduced by water saturation. Schmidt and

Graf (1972) demonstrated that asphalt pavement can lose as much as 50% of its tensile strength when saturated, although most strength was regained as the pavement dried. Humidity at realistic levels (e.g. 80%) reduces pavement performance, and aged pavement appears to be more vulnerable than freshly laid. In lab simulations of pavement aging at varying levels of humidity (Yu et al. 2013), creep stiffness increased at high humidity and failure temperature decreased. Forms of deterioration unrelated to fatigue (shoving, pothole formation, raveling, bleeding) are also aggravated by water (Adlinge and Gupta 2010). Some mechanisms of water deterioration are based on chemical change, whilst others are primarily physical processes. Damage may occur within the asphalt binder or between the binder and the aggregate; water reduces both adhesive and cohesive strength (Little and Jones 2003).

At a molecular level, water breaks the chemical bond between the asphalt binder and the aggregate in a process known as “stripping” (Kim and Lutif, 2006). Weak dispersion forces between binder and aggregate are easily displaced by the strongly polar water molecules (Little and Jones 2003). The degree of binder/aggregate detachment depends on the chemical composition of a particular aggregate material. At pH below approximately 4.0, amines are easily dislodged and a $CaCO_3$ (limestone) aggregate would be dissolved. To some extent, stripping can be mitigated by composition of the pavement mix. High pH binders are less prone to stripping than low pH binders, and more viscous binders are more prone than less viscous.

Molecular detachment leads to a thin film of water between aggregate and binder. Binder is then separated from the aggregate by the physical action of water in the micro-cracks (Willway et al. 2008). Water exerts pore pressure on the surrounding asphalt matrix due to mechanical compression by heavy traffic ("pumping"); the rate of crack formation is proportional to the number of load cycles (Little and Jones 2003). Mechanical pumping can lead to raveling and visible crack formation (Wolters 2003; Dawson 2014). Raveling leads, in turn, to localized areas of deterioration and eventually total disintegration of the asphalt layer.

At a coarser scale, pore pressure potentially causes delamination of pavement layers and formation of potholes. Moisture may accumulate to form water-logged layers which weaken the sub-grade and reduce the load-bearing capacity of the soil (Dawson 2014). Non-homogeneity in pavement courses causes uneven distribution of stress potentially leading to pavement failure (Rahman et al. 2011).

Freeze-thaw cycling

Moisture aggravates pavement deterioration in freezing temperatures. Ice forming in pores or cracks exerts pressure on the surrounding pavement matrix expanding existing cracks and initiating new ones. Lab trials show that freezing of pore and crack water exerts abrupt dilation strain on pavement over a period of 1-3 minutes as temperature declines (Lamothe et al. 2015). Water-saturated pavement samples showed significantly greater elongation, dilation, and contraction than dry samples.

Cycling between freezing and thawing temperatures (as occurs in spring and fall) can crack pavement through fatigue and aggravate micro-crack formation by other processes (Jackson and Puccinelli, 2006) - a form of damage not considered in the California study of McPherson and Muchnick (2006). Ice formation can cause stripping and raveling effects similar to thermal or traffic-induced stripping at higher temperatures (Dawson 2014). In laboratory trials, compressive strength and resilience to fatigue declined 20% over just 14 freeze - thaw cycles (Si et al. 2014).

If water penetrates the sub-base and freezes, expansion of soils (frost heaving) can exert pressure on the pavement from below (Quiao et al. 2013). Thawed sub-base soil may be waterlogged, creating an unstable base. Not surprisingly deterioration of roads in northern states is most rapid in the spring. Alternatively, soil moisture may be beneficial to pavement condition in some circumstances. Maintaining moisture in clay soils potentially avoids shrinkage in the foundation layer, maintaining load-bearing capacity (Willway et al. 2008).

Environmental effects, especially climate, are the leading causes of pavement deterioration and failure. Pavement degradation by thermal cycling, aging, and moisture penetration all depend on exposure to the open sky – the source of solar radiation and precipitation – so it is reasonable to assume that tree canopies, which block the sky, would mitigate such damage. Shade reduces thermal loading, potentially reducing the tensile stress in the surface layer caused by expansion and contraction. To the extent that pavement aging contributes is caused by UV radiation and temperature, shade trees potentially delay aging and maintain tensile strength (Adlinge and Gupta 2010). Trees may protect pavement from moisture-related degradation by catching a substantial amount of precipitation on leaves and stem and discouraging condensation (dew) formation. A more stable microclimate under a tree potentially reduces freeze - thaw cycling and, thus, protects pavement.

It is more difficult to make the argument that trees promote pavement degradation. It is, however, possible that trees would aggravate moisture-driven forms of degradation by delaying evaporation in the shade of the canopy. Undoubtedly all of these processes work simultaneously, but the relative importance of each in a real pavement situation remains to be determined. Some insight can be gained indirectly from ecosystem-level studies of trees in the urban environment.

Trees in the Built Landscape

Many studies have focused on the problem of widespread and persistent heat build-up in urban landscapes and the potential role of street trees in mitigating such build-up. As a result tree microclimate has been measured more often and with greater precision in urban studies than in natural forest settings. Much of this work is motivated by concerns about the effect of temperature on human health, but the results are also relevant to pavement condition. To the extent that this work specifically examines tree microclimate in paved areas, it casts light on the question of tree/pavement interaction.

Urban heat islands

Urban areas, which are dominated by masonry and pavement, absorb and re-radiate large amounts of solar energy creating city-sized zones of elevated temperature described as “urban heat islands” (Akbari et al. 1990; 1992). Radiant heat from pavement is controlled by thermal conductivity and substrate heat capacity (Quattrochi and Ridd 1994; Hardin and Jensen 2007). Pavement has a higher surface heat conductivity than soil, but a lower surface heat capacity (Landsberg 1981). In other words, pavement can radiate heat away from a lighted surface faster than soil and has less capacity to store heat, leading to faster heating of air above pavement.

Typically, 29-45% of an urban area is covered with paving material (Golden 2004), creating a large daytime heat sink. For example remotely sensed surface temperatures near Terre Haute, Indiana, reached 39oC in treeless urban areas but only 21oC in nearby forest in June 2002 (Hardin and Jensen 2007). In Ezurum, eastern Turkey, asphalt concrete in early afternoon in summertime was 6.5°C warmer than dry soil and 11.8°C warmer than grass-covered soil, leading to a 5.2-7.5°C elevation in air temperature over pavement (Yilmaz et al. 2008). In Phoenix, Arizona, pavement (67°C) was considerably warmer than air (38°C) at mid-afternoon in late summer, but pavement and air had almost equilibrated by dawn of the next day (Stempihar et al. 2012). Pavement consistently shows higher surface temperatures than unpaved ground in many studies (Bowler et al. 2010). Heat retention is proportional to pavement thickness, with thicker layers heating more slowly in the day and cooling more slowly at night. Acting at the scale of the whole developed area, this process can substantially increase the ambient air temperature relative to nearby rural areas.

The distribution of pavement defines hot and cool zones within an urban area. In Taipei, Taiwan, parks were found to have cooler air temperatures than surrounding urban areas (Chang et al. 2007), but the size and configuration of green space strongly modified this result: Large parks were cooler than small ones, and parks with little pavement were cooler than extensively paved parks (e.g. sports areas).

At the regional scale, the effect of pavement can easily be detected through remote sensing and satellite imagery of urban and nearby rural areas. A study of the Zhujiang Delta, southern China (Weng 2001) using Landsat TM infrared imagery reported that urban land cover had an average surface temperature of 70°C (158°F) while nearby farmland averaged only 39.8°C (104°F). In Utrecht, the Netherlands, the city center was consistently 0.3-1.5°C warmer in midsummer than grassland outside the city (Klemm et al. 2015).

Tree shading and pavement temperature

Heating of pavement depends on direct solar irradiance; thus pavement will be cooler under a tree canopy (Shahrestani et al. 2015). Temperature reduction is beneficial to humans because it reduces cooling costs and lowers ambient air temperature (Akbari et al. 2001). Urban trees also cool air by evapotranspiration of water from their leaves, and vegetation blocks adventive energy transfer (wind) from other areas, although these effects are generally less important than simple radiative heating from the ground.

Numerous studies have compared solar heating between shaded and unshaded sites in urban settings. However, it was beyond the scope of this review to comprehensively search the body of research on this area, but fifteen recent and/or widely cited examples are listed in Table 1.

Table 1. Tree shading affects pavement, air temperature, and humidity in urban settings

Study	Medium	Location	Maximum temperature	Temperature reduction	Humidity increase	Mitigating factors
Mascaro 2012	asphalt	Passo Fundo, Brazil	52 °C	9-10 °C		Foliage density
Golden et al. 2007	asphalt	Phoenix, Arizona	64 °C	11-25 °C		Tree species, Canopy density
Napoli et al. 2016	asphalt	Florence, Italy	NA	13.8–22.8 °C		Tree species, LAI
Armson et al. 2013	asphalt	Manchester, England	53 °C	7-16 °C		Tree species, LAI
	air		30 °C	3.8-5.0 °C		Not tree species, Not LAI
Vailshery et al. 2013	asphalt	Bangalore, southern India	55 °C	7.5-22.0 °C		Time of day
	air		35 °C	0.9-3.0 °C		Time of day
Gillner et al. 2015	asphalt	Dresden, Germany	49.4 °C	5.5-15.2 °C		Tree species, Tree size
	air		40 °C	0.8-2.2 °C	1.1-6.5%	Tree species
Scott et al. 1999	asphalt	Sacramento, California	> 60 °C	> 20 °C		
	air		41 °C	1-2 °C		Height
Klemm et al. 2015	asphalt	Utrecht, Netherlands	57 °C	≤ 4.8 °C		Presence of trees
	air		26 °C	0 °C		
Coutts et al. 2016	asphalt	Melbourne, Australia	54 °C	0-6.5 °C		Time of day
	air		27.5 °C	0.2-1.9 °C		Time of day
Souch and Souch 1993	air	Bloomington, Indiana	29 °C	0.7-1.3 °C	27-33%	Time of day, Canopy cover
Taha et al. 1989	air	Davis, California	29 °C	1.7-3.3 °C		
Parker 1989	air	Miami, Florida	NA	3.6 °C		
Georgi and Zafiriadis 2006	air	Thessaloniki, Greece	34.5 °C	1.7-7.8 °C	7-31%	Tree species, Canopy density
Zhang et al. 2013	air	Shenzen, southern China	31.8 °C	2.1-5.2 °C	6.2-8.3%	Vegetation growth form
Shashua Bar et al. 2010	air	Tel Aviv, Israel	33.7 °C	2.9-4.0 °C	4-7% VP	Foliage density, Planting density

Several effects are immediately apparent. First, solar-heated pavement can become quite warm.

Daytime pavement temperatures above 50°C (122°F) are not unusual, reported from southern Brazil, central Arizona, northern England, southern India, central California, the Netherlands, and southern Australia (respectively, Mascaro, 2012, Golden et al. 2007, Armson et al. 2013, Vailshery et al. 2013, Scott et al. 1999, Klemm et al. 2015, Coutts et al. 2016). Urban air temperatures can also be quite high (e.g. 41°C (~106°F) in Sacramento, California; Scott et al. 1999), but studies which measure both air and pavement consistently find that air temperatures are well below the corresponding pavement temperatures (Armson et al. 2013, Vailshery et al. 2013, Gillner et al. 2015, Scott et al. 1999, Klenn et al. 2015, Coutts et al. 2016).

Pavement temperature is consistently lower in the shade than in adjacent open areas in all studies reviewed here (Table 1). Shade can reduce pavement temperature by as much as 11-25°C (20-45°F) relative to temperatures in nearby unshaded areas (Akbari et al. 1997). Temperature is more commonly reduced between 5-25°C (41-77°F), with maximum differences observed in early afternoon (e.g. Vailshery et al. 2013, Coutts et al. 2016). Similarly, shade reduces air temperature above pavement relative to nearby unshaded sites. Simpson (1998) estimated that midday air temperatures in urban areas can be reduced 0.04-0.2°C for each 1% of canopy cover. Thus thermal cycling is less pronounced in the shade of buildings or trees (Golden et al. 2007). As an indirect benefit, experimental planting shows that houses shaded by trees experience a 26-47% reduction in cooling energy demand (Akbari et al. 1997). Consistent with radiative heating from the pavement, midday air temperature is most similar to pavement temperature near the ground and becomes progressively cooler with height (Scott et al. 1999; Stempihar et al. 2012).

Not all shade is equal. The radiation-blocking capacity of a tree canopy appears to vary considerably (Table 1), with the degree of pavement or air temperature reduction determined by foliage density and canopy structure (Mascaro 2012, Golden et al. 2007, Napoli et al. 2016, Souch and Souch 1993, Georgi and Zafiriadis 2006, Shashua Bar et al. 2010, Zhang et al. 2013). In many cases, contrasts in foliage density can be traced to differences between species; some species block significantly more light than others leading to lower pavement temperatures (Napoli et al. 2016, Armson et al. 2013, Gillner et al. 2015, Georgi and Zafiriadis 2006, Zhang et al. 2013, but see Souch and Souch 1993). In Thessaloniki, Greece, for example, air temperature reduction beneath the canopy differed substantially between species, ranging from a low of 4.9% under the loose, open canopy of *Albizzia julibrissin* to 22.6% under the dense canopy of *Brussenetia paperifera* (Georgi and Zafiriadis 2006).

Pavement and air temperature can also be linked to the height and crown size of individual trees (Gillner et al. 2015, Souch and Souch 1993). In Bloomington, Indiana, zones at the edges of tree canopies were intermediate in air temperature between fully shaded and open locations suggesting a gradient of solar heating with canopy position (Souch and Souch 1993). In Terre Haute, Indiana, Surface temperature was linearly related to canopy density, increasing approximately 1.2°C for every unit decrease in LAI, (Hardin and Jensen 2007). A recent study in Shenzen, China, (Zhang et al. 2013) compared strongly contrasting vegetation types in their capacity to block radiation: Mixed palm species (family *Arecaceae*) blocked approximately 50% of solar radiation, whilst a multi-layer *Araucaria* community, more similar to species found in Ohio, blocked approximately 90%. Bamboo (family *Gramineae*) was ineffective. Thus, incremental differences in canopy structure and density can affect the degree of pavement heating, and differences in structure between species are sufficient to create detectable differences in heating.

It has been suggested that the degree of temperature reduction by shading is greater in arid and tropical climates than in the moist temperate zone (Klemm et al. 2015), but there are several striking counter-examples (e.g. Armson et al. 2013, Napoli et al. 2016). It appears that broad geographical effects are overwhelmed by the idiosyncratic features of individual study sites.

Landforms and solar exposure

In addition to shading by trees, solar exposure is controlled by the position of land forms and buildings. In some cases, urban geometry and land forms appear to be more important to pavement heating than the presence of trees. A study in Colombo, Sri Lanka, (Johansson and Emmanuel 2006) found the most severe heating in wide streets with a low building profile (allowing maximum solar exposure) and no shade trees. Conversely, the least solar heating was found in narrow streets flanked by tall buildings and trees. Proximity to the seafront also reduced heating by increasing exposure to wind.

In Melbourne, Australia, the effect of tree cover on air temperature varied depending on neighboring buildings, with the greatest cooling value of trees observed in wide streets flanked with low buildings (Coutts et al. 2016). In London, England, (Shahrestani et al. 2015), pavement surfaces varied by 15-20°C (59-68°F) in the 24 hours of a summer day, reaching a maximum of 44°C (111°F) in one case. Building orientation relative to the sun and building spacing were the controlling factors because they determined the duration of solar exposure – presence of trees was only secondarily important. In a second study from Melbourne, Australia, orientation of a street relative to the sun affected urban air temperature by as much as 8°C (46°F), again reflecting solar exposure, (Sanusi et al. 2016). Based on these observations, future studies of pavement weathering must consider pavement location defined by both buildings and by trees, and the position of a particular road section in the landscape.

Moisture and humidity

Most studies of urban tree shading have been performed in dry and warm climates with little seasonal variation described as "Mediterranean" climates; less is known about urban microclimate in seasonally wet and cold regions such as Ohio (Coutts et al. 2016). Because water plays an important role in pavement deterioration, failure to consider moist regions is a serious omission. Several studies have considered humidity in urban settings, however, and a few have examined rain interception, so it is possible to speculate. The urban forest has been reported to intercept 15-27% of rainfall, preventing a proportion of rain from reaching the ground and potentially reducing standing water on pavement (Crockford and Richardson 1990, Xiao and McPherson 2002, Xiao et al. 2008). Deciduous trees monitored in Oakland, California, intercepted 14-27% of rainfall over a 7-month period (Xiao and McPherson 2011). The degree of water capture and diversion differed between species. The steep branching angle and smooth bark of sweet gum allowed faster runoff than ginkgo. In deciduous species rain interception was naturally greater in summer, when trees were in leaf, than in the winter. The water holding capacity of the crown was exceeded in large storms, so pavement protection is only available in small-moderate rainfall events. However a leafy canopy substantially reduced the amount of rain reaching the pavement when rainfall was distributed among many small events. In light rainfall, a tree canopy may completely protect the ground beneath although surrounding pavement is thoroughly wetted (GRM personal observation).

Relative humidity is commonly higher under the urban tree canopy (Table 1), confirming observations of trees in forests. Humidity can be as much as 27-33% higher under street trees than in nearby urban areas without a canopy (Souch and Souch 1993) suggesting that trees delay evaporation of pavement moisture. Georgi and Zafirdis (2006) reported 31% higher humidity under trees relative to open urban sites in Thessaloniki, Greece. On an individual tree basis, relative humidity correlated with the amount of light penetrating the canopy, which was related to species identity. However, 4-8% higher than adjacent areas appears to be more typical (Table 1).

These results demonstrate that the microclimatic effects observed in natural forests also apply in human-created landscapes. Indeed, solar radiation produces more extreme heat variation in urban landscapes due to the thermal properties of pavement. The ranges of temperature and humidity described in urban studies are similar to ranges determined to be critical in studies of pavement performance, suggesting that tree shading is relevant to pavement condition and service life.

Trees Affect Driver Behavior and Road Safety

The question of roadside trees and road safety is more complicated than it appears at first. Trees affect driver perception and behavior and potentially prevent formation of ice in late winter. Trees help to define the pedestrian and vehicle sections of the street, and protect pedestrians from hazardous vehicle behavior (Duany et al. 2000; Dumbaugh 2005). Similarly, tree canopy alongside and overtop the roadway can affect the condition of the pavement surface potentially affecting road safety. Some potential highway safety concerns related to tree canopies include the following:

- Fallen leaves on the road surface can potentially reduce the skid resistance.
- Trees slow traffic by making drivers more cautious.
- The lack of direct sunlight promotes formation of black ice in the late winter and early spring.

- Shade may influence formation of fog. Overnight condensation (dew) can freeze forming a thin layer of ice that creates one of the slickest road conditions.
- Nighttime reflection of heat by the canopy can reduce condensation and prevent ice formation under trees.
- Overgrown and aging branches can potentially fall on passing vehicles or block the roadway.

Trees as obstacles

At the simplest level, trees are obstacles blocking cars that run off the road (AASHTO 2011; Roadside Design Guide). So, while traffic engineers acknowledge that trees can be an asset, they also point out that trees are the "*single most commonly struck objects in serious roadside crashes*" (FHWA 2006). Crashes with fixed objects such as trees account for an estimated 1.9% of all crashes and 46% of crashes with fixed objects are fatal (Dixon and Wolf 2007). According to a FHWA study, car/tree collisions accounted for more than 4,000 fatalities and 100,000 injuries in the U.S. each year (FHWA 2006). In 2003, collisions with roadside objects accounted for >20% of highway fatalities (NHTSA accessed 12/16). A survey of vehicular crashes in the state of Washington over a four-year period showed that trees were involved in 4.2% of injuries (Holdridge et al. 2005).

To put this in perspective, concrete barriers were involved in 28%, guardrails were involved in 17%, and utility poles were involved in 11% of injuries, respectively. Trees were involved in 17% of fatal crashes, whereas concrete barriers played a role in 30%. In addition, the chance of injury was substantially increased due to factors such as high speed, DUI, and failure to wear a seatbelt. At a national level youthfulness of the driver and male gender also contribute significantly (Wolf and Bratton 2006). In 1996, the leading category of road-departure fatalities (27%) involved collisions with trees at high speed (>55mph) on major (50%) and rural roads (63%; National Highway Traffic Safety Administration: Fatality Analysis Reporting System). Predictably, driver condition was a major contributing factor (DUI in 48% of cases).

Collisions with fixed objects (especially trees) are more frequent in rural areas than in urban areas (Bratton and Wolf 2005). In fact, while 62% of annual miles traveled are in urban areas, 61% of crashes with trees occur in rural areas (Wolf and Bratton 2006). The proportion of roadway departures varies from 25% to 52% for all crashes occurring on rural two-lane highways (Lord et al. 2011). The experience in Ohio has been similar: In 2014, 59% of Ohio highway fatalities involved departure from the roadway, 53% involved a single vehicle, and crashes predominantly occurred in the most rural counties (NHTSA accessed 6/16). Crashes with roadside trees appears to be a rural phenomenon; comparisons of rural and urban areas show statistically significant lower incidence of crashes in urban areas with trees than those without (Lee and Mannering 2001).

The contribution of trees as roadside hazards appears to be specific to road type, location, and driver condition. To imagine a realistic scenario, it appears that collisions with trees occur when intoxicated drivers drive at high speeds along major rural highways. Conversely, trees along urban and small rural roads are unlikely to be involved in collisions because drivers are usually driving at lower speeds.

Road condition

The most basic function of a pavement's surface course is delivery of a safe and comfortable ride for the road user (Adlinge and Gupta 2010). To do this, the pavement must have specific functional characteristics such as good skid resistance and texture depth; and it must minimize noise and provide a smooth ride. In locations where the pavement has degraded due to environmental conditions, functional efficiency may be compromised.

In the short term, trees potentially affect road surface conditions by altering the road microclimate including surface wetness, snow, and ice. If trees shelter pavement from rain or snow, surface friction will be maintained in poor weather. Alternatively, if trees prevent thawing and drying of pavement, surface friction may be compromised.

Several million dollars are spent on snow removal in Ohio annually amounting to $3,052 per lane mile in cities (ODOT 2011), reflecting the potential danger caused by impeded road surfaces. However, only 18% of fatalities occurred on slippery roads, suggesting that road condition is not the most important consideration (U.S. Department of Transportation's Fatality Analysis Reporting System). This is consistent with Holdridge et al.'s (2005) observation that presence of snow, ice, or darkness actually decreased the likelihood of road-departure injury, presumably because drivers drove more cautiously. It is notable that substantially fewer fatal crashes occur in the presence of snow, ice, and rain than on dry days (NHTSA accessed 6/16).

In the long term, pavement degrading (aging, stripping, rutting) directly affects the safety and comfort of the road user. Short-term road surface effects may interact with long-term pavement condition. For example, rutting is known to trap water and thus increase the possibility of hydroplaning and poor visibility as a result of spray. Strat (1998) suggested that 7.6 mm (0.30 in) rut depth is the point at which significant increase in accident frequency starts to appear. Research by Chan et al. (2010) suggests that for regions with more precipitation, rutting should be considered as an important safety measure. It is still unclear how trees affect pavement condition. Cenek et al. (2014) show that crash rates decrease slightly under trees, particularly for dry crashes. This may reflect the sheltering effect of tree canopies. Conversely, in the absence of trees, water accumulates on the unsheltered road surface potentially affecting traction and a driver's control. It is possible that low crash rates are simply an artifact reflecting high tree frequency along low-speed roads where serious crashes rarely occur.

Aging and stripping will cause a loss in pavement skid resistance and, thus, affect the safety of drivers. There is a particularly high potential for crashes in regions where skid resistance is further reduced by snow and ice in winter months (as in Ohio). The 1999 statistics from FARS show that for two-lane, undivided, non-interchange, non-junction roadways, 11% of single-vehicle ROR fatal crashes occur on wet roadways, with 3% more occurring on roadways with snow, slush, or ice (NHTSA, 2001). In fact, a water film thickness of 0.002 inches reduces the tire pavement friction by 20 to 30% of the dry surface friction. Data presented here suggest that trees have the potential to reduce surface wetness but the effect on traffic safety remains to be tested.

Safety is an even greater concern on curved roadway sections where unprepared drivers can easily run-off-the-road if the pavement surface is slick, effects which will be proportionally worse in the dark. Traffic crash occurrence has been studied from different perspectives, such as highway geometrics, vehicle condition, driver condition, and traffic condition. However, relatively little research is available on traffic safety related to pavement distress prevented or caused by tree canopy. Locations under tree canopies have less light from the moon, stars, and nearby light fixtures and would therefore affect the driver perception of objects as they travel. This can be a particular issue on curved sections of roadway with relatively high speeds. This can also be an issue on a bright, sunny day as drivers traverse through heavily canopied sections of roadway. Drivers are likely to experience a "tunneling" effect and their eyes will take some time to adjust to the differences in light conditions.

Trees and driver behavior

The above discussion is largely based on crash statistics, and does not actually test the idea that roadside trees are responsible for causing crashes or that tree removal would reduce crashes. In fact, research studies present mixed results regarding the presence of trees and their impacts on driver behavior and subsequently crash frequency. Recent driving simulator based studies suggest roadside trees do not cause drivers to adjust their driving speed; possibly due to trees not being perceived as a threat to safety by the drivers (Bella and Tulini 2010; Jamson et al. 2010; Abele and Moller 2011; Bella 2013).

On the contrary, several studies suggest that presence of trees actually influences driver behavior and subsequently reduces crash frequency. The effects of trees on roadway safety were experimentally tested by placing trees and planters along the roadsides and medians of arterial highways in Toronto (Naderi 2003). The author found a statistically significant reduction in the number of mid-block accidents, amounting to reductions of 5-20% in the sections lined with trees. A study of ten urban arterial road sections in Texas showed a statistically significant 70.8% reduction in crash rate after roadside trees were planted (Mok et al. 2006). A comparison of twelve multi-lane road sections in the Middle Atlantic region showed significantly lower number of fatalities in sections with roadside trees presented and lower cost of accidents than sections without trees (Mok and Laudphair 2002).

Improved road safety in tree-lined sections may be related to reduced speed. Results from trials in a computer driving simulator (Naderi et al. 2008) indicated that the street tree effect may provide positive safety benefits for drivers. The average speed of 31 drivers was found to be 3.02 mph (4.9 kph) slower in the presence of roadside trees in a suburban landscape (both fast and slow drivers showed a reduction) possibly because trees improved road edge definition. A similar study in Sweden, showed significantly lower speeds on simulated tree-flanked roadways (Antonson et al. 2009).

More recently, Calvi (2015) showed that when trees were close to the road edge, drivers were found to decrease their speed significantly and move toward the centerline of the road whereas, when the offset of trees was increased, drivers adopted higher speeds that increased the distance from the road edge but with a lower left lateral displacement. Additionally, drivers moved farther away from the road edge when tree spacing was decreased. The results demonstrated that drivers balanced the useful guidance information that roadside trees provided with the risk associated with the presence of trees: when trees were far away, the sense of guidance was predominant, and drivers adopted higher speeds; when trees were closer, drivers saw the trees as a risk, slowed down, and moved further away from them.

These results were replicated in a real road setting in Norfolk, England. The planting of trees reduced average driving speed in four locations by approximately 2 mph (Roberts 2010). Reduction in speed is consistent with the general observation that mid-block (non-intersection) crashes, injuries, and fatalities are reduced in urban areas congested by pedestrians, parking, and street architecture (Ewing 1999; Ossenbruggen et al. 2001, Lee and Manring 2001, Dumbaugh 2005).

Little information has been published on treefalls across roads, although there is considerable anecdotal evidence. A study comparing traffic interruptions in the mountainous Czech Republic (Bil et al. 2016) ranked treefalls as causes of traffic interruption in 22% of cases, behind flooding (37%) but ahead of landslides (5%) and rockfalls (2%). Most obstructions were quickly cleared away, and caused no long-term interference with traffic. Clearly the relative rankings will depend on the geography of a particular region.

Practitioner Interviews and/or Surveys

The goal of this task was to solicit information and enable a comprehensive understanding of the specifics as they pertain to tree canopy (alongside and overtop roadways) and pavement condition, safety, and maintenance practices. For entities within Ohio (i.e., personnel at ODOT district offices and institutions/organizations with vested interest in the tree canopy concept), information was solicited via a telephone interview that lasted approximately 30 minutes. As for the DOTs in other states, a survey questionnaire was administered via email and follow-up telephone calls were made to: 1) clarify a particular response to the survey, and 2) gain more information about promising practices.

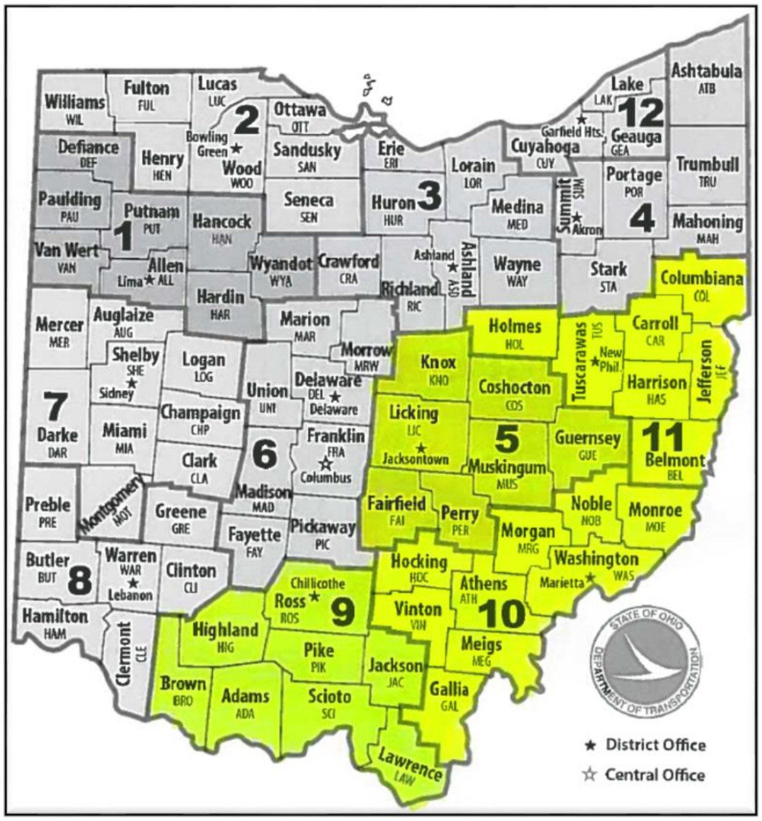
The research team developed a detailed e-mail request for participation as well as a list of specific questions to be asked during the interview and/or survey. This preliminary interview and/or survey framework was submitted to the Technical Analysis Panel at ODOT for review and comment. As well, this task involved the use of human subjects in research, therefore researchers obtained approval from the Ohio University Institutional Review Board (IRB) prior to proceeding with the interviews and/or surveys. The interview and/or survey questionnaire (attached as Appendix A) was structured to focus on the following topics:

- Effects of tree canopy alongside and overtop the roadways;
- Current tree canopy mitigation/management practices;
- Basis of current (adopted) mitigation/management practices; and
- Evaluations of current (adopted) mitigation/management practices.

Ohio Based Entity Interviews

Within Ohio, the researchers from Ohio University conducted interviews with staff from the following:

- Ohio Department of Transportation
    - Personnel from district offices 5, 9, 10, and 11 as depicted in Figure 2. Specifically, Highway Management Administrators, Pavement Engineers, and Studies Engineers.
    - Pavement Condition Raters.
    - Safety Engineers from the Highway Safety Program.
- Scenic Ohio – a non-profit organization dedicated to protecting and enhancing the visual quality and scenic character of Ohio's towns and countryside. Specifically, some members of the Board of Directors.
- Flexible Pavements of Ohio – an association that exclusively represents the interests of the asphalt paving industry in the state of Ohio to federal, state and local governments and other construction and business organizations.



**** Only personnel from highlighted districts were interviewed.**

Figure 2. Map of Ohio Department of Transportation District Offices.

The responses from the interviews were categorized according to the focus topics mentioned above and are discussed in detail in the sections that follow. A summary of the findings are presented in a matrix format in Appendix B.

(a) Effects of tree canopy alongside and overtop roadways.

Safety Related Effects

Most respondents mentioned there were safety concerns associated with the presence of tree canopy alongside and overtop the roadway. The concern that was prioritized was that there is accumulation of snow and/or moisture on roadway surfaces not directly exposed to sunlight. Where there is accumulation of snow, shaded roadway sections are the last locations to thaw and where there is accumulation of moisture, these surfaces freeze quickly during the winter. In both cases, the roadway surface becomes slick, has a reduced coefficient of friction, and is a hazard to the travelling motorist. Respondents noted that the moisture is not necessarily from snow and rain events but also from condensation dripping from tree branches. It was also alleged that fallen leaves stay damper in shaded locations and causing the pavement surface to be slippery (black ice presence). Additionally, it was believed that, because the shaded sections are for the most part short in comparison to unshaded sections, there could be many instances where drivers are comfortably travelling on long stretches of dry unshaded pavement and are then suddenly on a slick shaded pavement that can be potentially dangerous causing the driver to run off the road. In fact, District 10 reported that there was an instance when they used crash data (i.e. run-off-the-road due to ice and collision with trees) to successfully obtain some funds for tree trimming exercises.

The next concern of priority for many of the respondents was the issue of falling debris on roadway segments having canopy overtop or alongside. Falling debris in the form of trees and/or branches posed a threat of causing road closures and sometimes even fatal and/or injury crashes. For example, in District 5, there were two reported fatalities in recent years where motorists had struck trees that had fallen in the roadway. The cause of these fallen trees and/or branches was reported to include age, disease, soil conditions (shallow rooted), or trees leaning towards the roadway. Where trees are located on the side of slopes, there was also the potential of the slope sliding and dropping the trees onto the roadway.

Other concerns raised were related to issues with fallen leaves. Especially on two-lane roadways, it was thought that fallen leaves covered the edge line markings and this could potentially become an issue for motorists in foggy conditions. There is also the issue of the fallen leaves clogging the drainages for the roadway segments in shaded areas. Also of concern was the somewhat “tunneling” effect that roadways with a mix of shaded and unshaded segments had on drivers. It is believed that as drivers transition between shaded and unshaded segments, they are subjected to changes in their driving behavior because their perception of road width is altered (sense of narrowness created), luminance is limited, and sight distances are restricted.

The items mentioned above relate to aspects of having canopy alongside and overtop roadways that are claimed to adversely affect safety however, it is thought that there are also positive aspects. Some respondents believed that, in their experience, roads with canopy do not pose any problems such as early icing or black ice and the air moisture circulation caused by the tree canopy is probably a good reason for no negative impacts. In fact, it was thought that driving through a canopy is a pleasant experience and it makes drivers go slower, is a good safety precaution, and develops happier neighborhoods. These positive effects have been demonstrated on scenic routes and neighborhoods (e.g. City of Gahanna).

Pavement Condition Related Effects

Respondents stated that tree canopy alongside and overtop the roadway is definitely responsible for distress on the pavement surface. It is believed that, more often, shaded segments were observed to suffer from *raveling* – progressive disintegration of a HMA layer from the surface downward as a result of the dislodgement of aggregate particles. The raveling was observed primarily on the wheel path and there were also reported cases of severe edge raveling. Respondents thought the pavement surface experienced accelerated degradation in shaded sections due to moisture remaining on the pavement for longer periods. The ODOT districts reported that many of their milling/surface coarse operations (patching, overlays) were in locations with shaded pavements due to thick canopy.

It was also believed there was a phenomenon of "wet shade stripping" that occurred on canopied roads. This is essentially the separation and removal of asphalt binder from aggregate surface due primarily to the action of moisture and/or moisture vapor. According to one of the respondents, it was understood that, in Georgia the pavement was resistant to stripping in regions not exposed to direct UV light however, in Ohio there was accelerated damage to shaded sections. This was attributed to the stripping test being very subjective and that no stripping additive is added to HMA mixes in Ohio.

Respondents also felt that, in shaded sections, the structure of the pavement was susceptible to damage due to moisture permeating through cracks. This was attributed mainly to the rapidly changing microclimate (freeze/thaw cycles). Whereas, HMA mixes used by ODOT are designed to accommodate extreme temperatures, and typically a PG Grade of 64–22 is used, but the effects of rapid and cyclic changes in surface temperature is of concern here. The pavement becomes prone to thermal cracking and therefore moisture will permeate down to the substructure and cause damage to the roadway in the form of potholes. In sections where the drains are clogged (due to fallen leaves as stated above), there is a likelihood that excess moisture remaining in the base layers will cause damage to the pavement matrix.

Respondents also referred to some construction related concerns. There was discussion of concerns with differences in compaction (and possibly density) between shaded sections versus exposed sections. In sections exposed to sunlight, the compaction of the subgrade is likely to be more standard then in shaded sections. Also, during the placement of overlays/patching, the surface condition of the existing pavement is different between the shaded and unshaded sections. Additionally, HMA mixes are likely to cure differently between shaded and exposed sections. Respondents believed these differences in compaction density, existing surface condition, and differential setting are likely to affect the life expectancy of pavement overlays/patching/resurfacing. Lastly, concerns of falling leaves (in shaded sections) during resurfacing or tack coating operations that affect the quality of the tack coat were also raised.

One last concern with regard to pavement condition was the issue of tree resins dripping onto the pavement surface. There is a high likelihood for the resins to cause a change to the chemical properties of the asphalt and subsequently affect the pavement surface condition. This is particularly the case in section where Oak trees are present.

Maintenance Related Effects

Respondents reported that roadways with canopy alongside and overtop also had maintenance related issues with the most notable being; added use of salt/deicing agents and added costs of routine maintenance. As mentioned earlier, there was a safety concern with accumulated moisture (freezing and/or delayed thawing) on shaded pavement sections. To protect travelers from driving on a slick pavement surface, it is general practice for maintenance crews to spread salt and/or deicing agents over the roadway. Due to the pavement remaining much colder in shaded locations, respondents mentioned this affected their snow maintenance operations. Essentially, there is relatively higher usage of salt and/or deicing agents for shaded pavement sections in comparison to pavement sections that are exposed to sunlight. The excess salt/deicing in shaded sections is costly, can affect the pavement, and also the environment.

The ODOT districts reported that shaded sections of roadway were often prone to raveling and therefore required resurfacing/patching/overlays. These forced maintenance operations were performed at an additional cost. Also, fallen leaves clogged drainage structures in shaded sections and so routine cleaning was required which placed additional maintenance costs.

The above safety, pavement condition, and maintenance related effects are based on observations of the interviewees and are mostly anecdotal. Respondents noted that, to their knowledge, there was no research providing any empirical or scientific evidence into the effects of tree canopy overtop or alongside the roadway. All of the respondents were very much interested in the results of a detailed and research motivated study into the effects of tree canopy on roadways.

(b) Current mitigation/management practices

Even with certain groups observing that tree canopy has positive effects to safety and pavement condition, the interviewed ODOT districts have taken a more conservative approach of focusing on the reported negative effects of tree canopy alongside and overtop the roadway. Therefore, the current mitigation/management practice adopted by the ODOT districts is to perform roadside tree removal and ground to sky trimming along routes and/or roadway sections identified as hazardous. Trees are cut back (or removed) 20 to 30-feet from the roadway centerline depending on the available right-of-way (ROW). Typically, the ODOT specifications suggest no trees within 10-feet of the ROW. In the past, districts have used contractors for tree trimming operations but have more recently been using a tree trimming machine (loosely termed the “giraffe”).

A challenge with cutting back the tree canopy (or tree removal) is that there is no guidance on protection. There exists an issue with areas beside slopes/hillsides, where canopy is removed/cutback getting into protected lands. However, the pavement still remains completely shaded by the slope/hillside. Also, the tree trimming, such as that on US-33 between Athens and Nelsonville, Ohio could even increase the hazards as the topped/hacked trees (mostly Silver Maple) will soon grow new vigorous tops which will now be attached to decaying trunks (O Ryan Gassaway, personal communication).

The ODOT districts are considerate of protected species, particularly the federally endangered Indiana and federally threatened Northern Long-eared bats, during their tree trimming operations. Specifically, there are strict restrictions to tree trimming during specific seasons in accordance to guidance provided in the "*Framework Programmatic Biological Opinion*" prepared by the U.S. Fish and Wildlife Service. As an example, ODOT District 9 perform tree-trimming operations from October 1 to March 31. Specific trees (e.g., Shagbark Hickory, Silver Maple, and White Oak) are preserved because they are used as roosts.

Advocates for having trees alongside the roadway do understand that trees go through limb loss however, they believe a specific tree selection process should be available. They suggest planting specific tree types alongside the roadway such as; American Sycamore, Hackberry, and London Plane. These trees are adaptable to the roadside, tolerant to the damage caused by salt from winter snow operations, and provide a scenic touch to the roadside.

Pavement repairs in the form of patching, applying overlays to damaged sections, and or resurfacing is commonly adopted to address the defects caused to the pavement surface.

(c) Basis of current (adopted) practices

For many of the districts interviewed, there is no specific guidance or formal process on how tree canopy alongside and overtop the roadway is to be maintained. The practice of cutting back trees adopted is based on AASHTO guidelines of providing a "forgiving" roadside clear zone for errant vehicles. The districts select routes or roadway sections that need to be trimmed based mainly on (i) reporting by county managers, and (ii) complaints from the public.

Only District 10 reported that in 2009, to acquire funding from the High Risk Rural Roads program to carry out tree trimming operations, they prioritized routes on the basis of tree related crashes and review from county managers. However, whether the selected crashes were directly related to tree canopy effects is somewhat questionable. In District 5, a Vegetation Management Plan has been adopted for the last three years. This Vegetation Management Plan provides some form of documentation for trimming operations within the district.

Pavement Condition Rating (PCR) is also used by the districts to select routes in need of pavement repairs. PCR provides a procedure for uniformly identifying and describing, in terms of severity and extent, the distress observed on pavement surfaces. Three levels of severity (Low, Medium and High) and three levels of extent (Occasional, Frequent, and Extensive) are defined. However, using the PCR values does not always indicate that a road segment is in need of repair due to the presence of a tree canopy, and instead the respondents usually rely on county managers' reports for areas that need maintenance.

(d) Evaluations of current practices

All of the interviewed districts claimed that trimming operations provided benefits to the safety, pavement condition, and maintenance of the roadside shaded by tree canopy. The reported benefits include;

- Reduced frequency in pothole patching operations;
- Reduction in usage of salt and/or deicers; and
- Improvement in safety.

However, these benefits are based on anecdotal evidence and no empirically driven research studies are available in support. District 10 reported their cost for tree trimming operations is approximately $5,400 per mile. Again, due to a lack of empirically driven research showing the benefits, it is not possible to have a clear idea of the benefits versus costs. In fact, some districts are interested in knowing if it was cost effective to perform trimming in comparison to pavement maintenance at shaded sections.

Using PCR as a means of selecting pavement sections that require maintenance will prioritize routes with a lower rating versus those with higher rating. However, with regard to tree canopy, it is likely that the PCR is not significantly affected by the shaded sections, since PCR is performed on 2-3 mile long sections. Therefore, within a 2-3 mile long section, there may only be a small (< 0.5 mile long) section with a tree canopy and thus will not alter the PCR rating significantly. PCR raters did mention that they will include in their notes that presences of damage under tree canopies if it is significant enough.

Other aspects of the current trimming practices that were raised by the districts included training, complaints, and aesthetics issues. Districts mentioned the need for guidance for their personnel on tree species – ability to identify trees, understand them, and know when to trim or not to trim. The districts referenced to the need for some kind of training from certified arborists or even including certified arborist(s) to give guidance to their maintenance crews. The districts did not mention having any public complaints to their trimming operations. Though District 5 did mention having some complaints from specific individuals such as from Ohio Arboriculture and a few villages in their area. There was also a concern with the trimming operations in that it left the roadside in a poor aesthetic condition. The roadside looked ugly and there is a potential for drivers to get distracted and take their eyes of the roadway.

State DOT Surveys

To complement the findings from Ohio, the researchers' determined to survey 11 state DOTs. These select DOTs were identified on the basis that they are located in regions of the U.S. that have climates similar to that experienced by Ohio. That is, relatively similar rainfall, average temperatures, and extreme temperature differentials. More specifically, the research team targeted the following DOTs including: District of Columbia, Illinois, Indiana, Kentucky, Maryland, Michigan, New York, Pennsylvania, Virginia, Wisconsin, and West Virginia. Responses were received from 7 out of the 11 DOTs (64 percent) as shown in Figure 3. A summary of the findings are presented in a matrix format in Appendix C.

Overall, all respondent DOTs recognized the topic of tree canopy alongside and overtop the roadway as something that is of current concern. Whereas canopy is understood to be due to trees in close proximity to the roadway, it is believed the orientation of the highway would also affect shading. That is, highways running predominantly in the east/west or north/south direction will tend to have predictable shading and associated issues on one or both sides of the roadway.

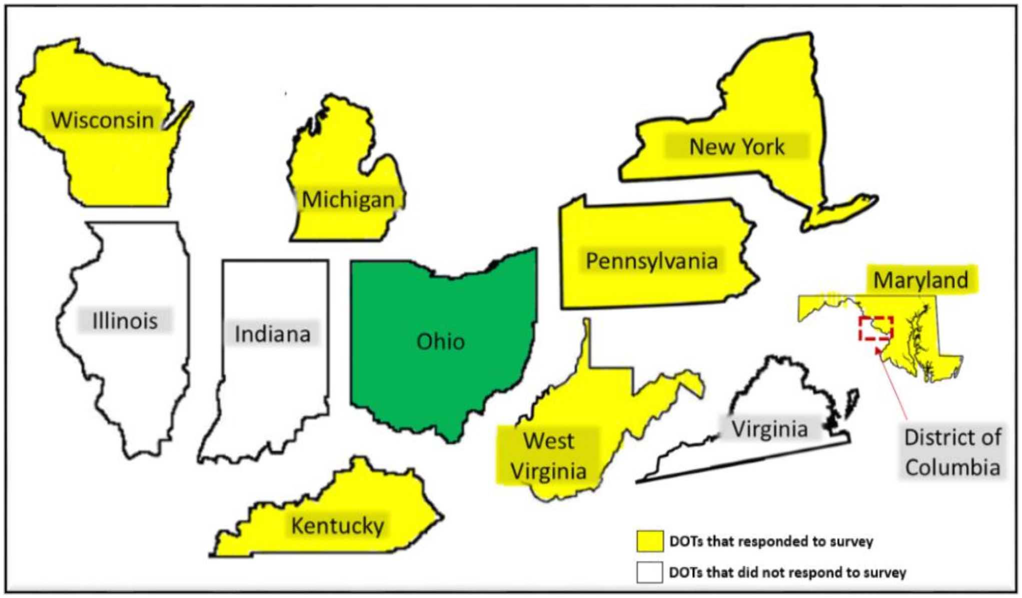


Figure 3. Geographical Orientation of State DOTs Targeted for Surveys.

(a) Effects of tree canopy alongside and overtop roadways.

Safety Related Effects

It was a general consensus among the state DOTs responses that shading from tree canopy alongside and overtop the roadway not only caused varying surface/subsurface temperatures but also affected the moisture (rain, snow/ice) levels. It was believed that shading can lower pavement temperatures and allow rain and/or snow/ice to remain on the pavement longer or be hard to remove. The snow/ice can pose a hazard to drivers who can be caught unaware by the inconsistent road conditions (i.e., pavement surface prior to and after the shaded area is dry and free of snow/ice while directly under the shaded area there is snow/ice present). In canopied areas, there can be dripping moisture that will take longer to dry out and can cause hydroplaning.

Respondents identified concerns with tree limbs on canopied road sections. The major concern was of whole trees or their limbs causing property damage, injury, or even death if they fall on the travel lanes or fall on vehicles. Pennsylvania and Kentucky reported that falling trees/limbs was a big concern for them because of the decline in tree health due to insects such as the Emerald Ash Borer and Wooly Adelgid. In areas where the tree canopy is low, there is a likelihood of the limbs causing damage to the tops of trucks or recreational vehicles. There were concerns of trees close to the roadside causing sight distance restrictions particularly for road signage and overhead advertising. Other safety related concerns was a lack of snow drift control in areas with tree canopy alongside the roadway as reported by Wisconsin DOT.

Not all aspects of tree canopy can affect safety negatively, as some DOTs reported that drivers attributed to some positives in support for tree canopy alongside and overtop the roadway. West Virginia reported that some drivers liked tree canopy because it had a “tunnel effect” whereas in Maryland, drivers viewed tree canopy positively believing it provided a “country” feel especially on two-lane roads.

Pavement Condition Related Effects

The DOTs iterated to the fact that the pavement holds moisture much longer on canopy covered (or shaded) sections than on those sections exposed to direct sunlight. This moisture can impact pavement preservation causing the pavement surface to deteriorate much sooner than expected. In West Virginia there was an observed increase of pavement defects (potholes, alligator cracking, and base failures) while Pennsylvania mentioned a reduction in time between resurfacing operations in canopy covered areas.

Maintenance Related Effects

Overall, it was reported that tree canopies can increase required maintenance. The major maintenance related concern alluded to by many of the DOTs was that of additional resources and subsequent costs to tackle winter snow operations. In canopy shaded sections, the lack of direct sunlight greatly reduces the effectiveness of salt and deicing chemicals. Therefore it is believed that shaded sections require additional deicing chemicals, labor, and equipment. There is even the possibility of a change in materials and product rates within the shaded areas.

In locations where the canopy is dense, there is a potential for increased fallen limbs that will require immediate clearing and frequency of paving operations. Many times, these additional clearing and paving operations which of course require labor and equipment, are not included in the routine maintenance budgets. Additionally, the clearing and paving operations, will require road closures and will cause disruptions to the travelling public.

West Virginia also reported a maintenance concern with respect to fallen leaves from canopy trees that caused clogged ditches, culverts, and drop inlets. Routine cleaning was required which placed additional maintenance costs.

(b) Current mitigation/management practices

The general course of action that the DOTs have in place to mitigate/manage the tree canopy are tree removal, ground-to-sky trimming, and/or tree limb thinning. These practices are, in some states (Kentucky and Maryland), supplemented with the use of herbicides and plant growth regulators.

All of the DOTs reported making considerations for protected species (bats, migratory birds) in their tree removal/trimming operations. Typically, any routine tree management is performed after consulting with protection agencies and occurs during seasons when the species are not present. In situations where tree removal/trimming is done on a case-by-case basis (with endangered species present) then priority is given to public safety and tree removed/trimmed.

The responses received suggest there is awareness within the DOTs of public/private groups (scenic byway groups, conservation groups, tourism initiatives etc.) that may have a vested interest in canopy covered/tree-lined roads. The interests of these public/private groups are commonly addressed through outreach meetings before trimming work is performed. These meetings serve to promote a collaborative understanding on the need for managing the tree canopy. This cooperation is especially necessitated in locations designated as scenic routes and designated protected lands such as New York's Adirondack and Catskill parks. One DOT referenced an instance when there was disagreement between a specified private group and the DOT's tree management goals. The resolve was to prioritize safety considerations above aesthetics.

(c) Basis of current (adopted) practices

The canopy maintenance practices were based on industry standards, existing laws, and guidance whereas the management practices (tree removal, ground-to-sky trimming, and/or tree limb thinning) were based on past experience and treatment. Many of the DOTs referenced the AASHTO *Roadside Design Guide* for their current tree canopy maintenance. Therefore, any removal of trees and also how far back the tree canopy must be cut back from the roadside are determined on basis of the AASHTO guidelines. Additionally, reference is also made to other industry standards such as the EPA's Integrated Vegetation Management process.

For many of the DOTs, the decision to continue tree canopy trimming is driven purely by past experiences. Many of the DOTs reported not having any program (or routine maintenance schedules) that address specifically tree canopy and its effects. Therefore a formal process of identifying projects (or prioritizing road sections) for mitigation or management was not available. Instead, tree canopy issues are dealt with continually on a case-by-case basis. That is, when a concern is received (from either public or local maintenance personnel), then crews are sent to address the issue. In fact, Pennsylvania uses Highway Foremen who each carry a chain-saw to remove tree debris as it is encountered. Only New York reported having a monitoring program in form of a "hazard tree survey" conducted twice a year that allows residency managers to identify canopy problems and locations that need attention.

The DOTs did highlight some challenges (or limitations) they faced with prioritizing projects for tree canopy maintenance and/or management. Some of these challenges include:

- Limited resources (money and labor) allocated for this problem;

- It is a tedious task to develop and execute any maintenance task, therefore trade-offs need to be made between canopy related work and other maintenance tasks that require immediate attention; and
- Budget allocations are shared among many maintenance activities such as winter maintenance and roadside operations therefore canopy related maintenance is low priority.

In situations in which a single tree was potentially hazardous, some DOTs reported having a tree assessment process. Therefore, is a public complaint is received about a specific tree, then the DOT will send a trained person (arborist, forester) who performs a field assessment of tree and makes recommendation after which a work order is submitted.

(d) Evaluations of current practices

All the DOTs reported that specific evaluations on their current tree management practices have not been performed. Therefore, any information on expenditure, effectiveness, best practices, and other measures was not available. Only Kentucky mentioned spending $3 million in 2016 for tree canopy management.

The respondents did cite some strengths and weaknesses in their current tree canopy management. The reported strengths include the ability to extend pavement preservation and address safety concerns quickly; and tree removal is a more permanent solution but not economical and acceptable.

The reported weaknesses of the current practices include; inconsistencies in keeping the canopy trimmed back and a major effort will be needed; pro-Canopy groups wanting to fund tree planting but neglecting the associated maintenance; and also that mechanical and chemical (side) treatment methods both need retreatment after a few years.

Some DOTs reported their personnel are lacking in knowledge of trees and recognition of hazard situations however others reported having (or wanting) tree experts on their maintenance teams.

“Test of Concept” Analysis.

As part of phase I of this project, the research team planned on performing a “test of concept” type analysis on a roadway section close to Ohio University. The objective of this task was to perform simple and very preliminary data collection protocols that would require no financial support but provide reasonable data to support conclusions for this phase of the project. Interactions with various personnel from ODOT districts 5, 9, 10, and 11, allowed the research team to identify a number of locations where sections of roadway had tree canopy alongside or overtop. However; due to time, budget, and proximity constraints, state route 356 (OH-356) in Vinton County, Ohio was selected for the “test of concept” analysis.

Description of Test Location

OH-356 in Vinton County, Ohio is a two-lane roadway that connects US-50 to the town of Mineral, and also to OH-56 which connects to New Marshfield and Athens, Ohio. As depicted in Figure 4, the landscape is dominantly forest with OH-356 (and other low volume surrounding roads) having a large amount tree canopy density.

There are significant portions of OH-356 having tree canopy alongside or overtop the pavement surface. Two sections of OH-356 (approximately 500-feet in length) were observed for any apparent differences due to tree canopy. Thus, the observed test location had at least 500-feet that was shaded (canopy on roadside or overtop) and at least 500-feet that was unshaded (exposed to direct sunlight). Specifically, pavement condition ratings (PCR) were compared. Figure 5 presents Google images of the observed sections of roadway. Note that the images were taken in August 2016 during the summer months and specifically the shaded versus the unshaded roadway is depicted by the presence of canopy (a) and no canopy (b).

Rating the Sections

The sections were rated according to the ODOT Pavement Condition Rating System (PCR) (ODOT PCR Manual 2006) and using the Distress Identification Manual for the Long-Term Pavement Performance Program (Miller and Bellinger 2014). The ODOT PCR manual specifies that the “… pavement condition rating is intended to apply to entire pavement section being monitored...with average length being from 3 to 5 km (2 to 3 miles).” When looking at distress on pavement sections with and without a tree canopy, the length of the section might mask some of the effects of the tree canopy due to the short length in which tree canopy is or is not present. On the other hand, the FHWA LTPP distress identification manual limits the survey sections to 152 meters (500 feet) in which case the effects of a tree canopy might be more apparent.

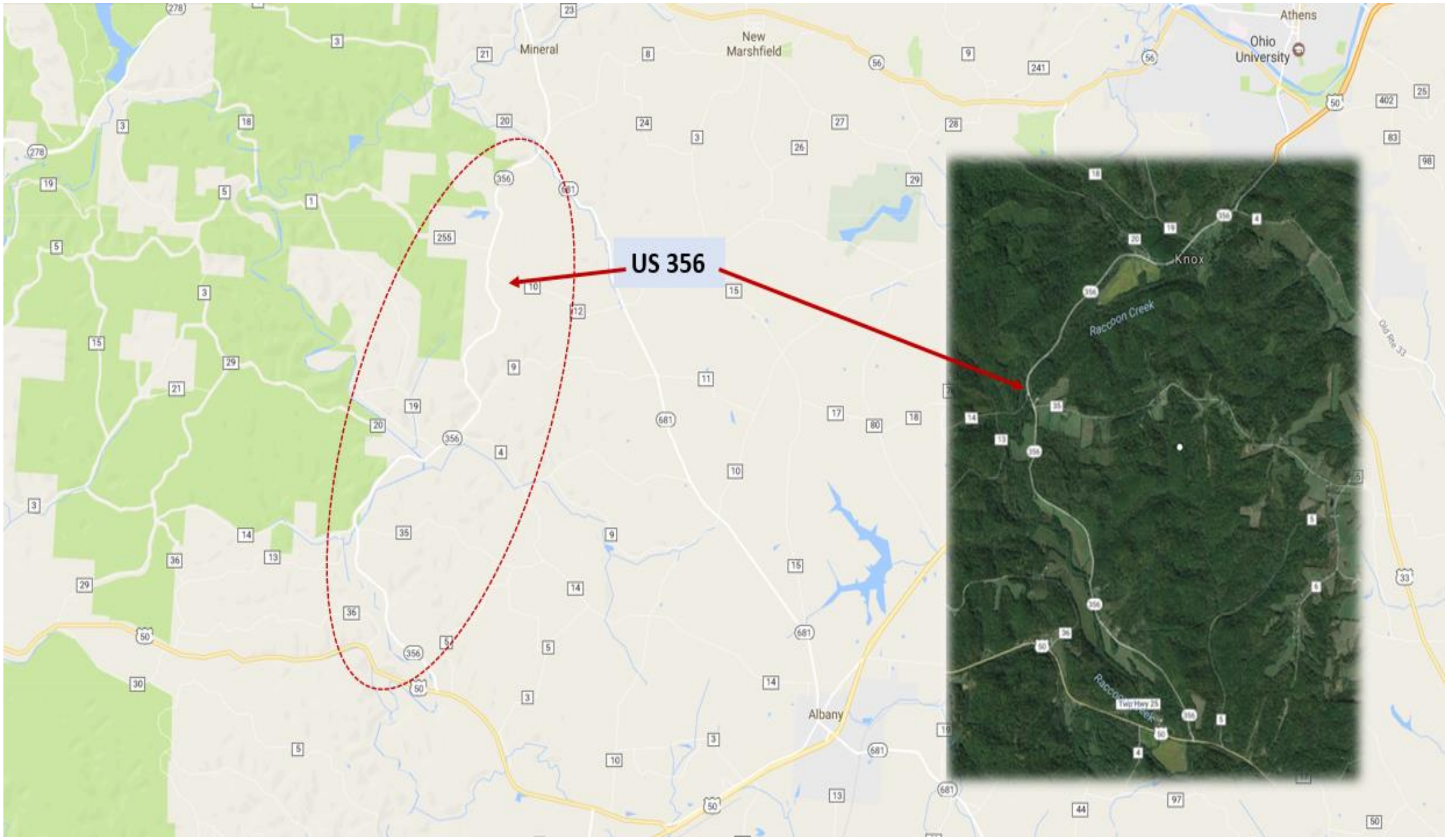


Figure 4. OH-356 Canopy Roadway in Vinton County, Ohio.

(a) Canopy covered section (b) Exposed section

Figure 5. Test Sections of OH-356 in Vinton County, Ohio.

The ODOT PCR rating tables for the sections on OH-356 are shown in Table 2 and Table 3, the FHWA LTPP field distress notes were scanned and are shown in Appendix D.

Table 2. ODOT PCR rating: no canopy section (OH-356)

Section: NO CANOPY
Log Mile: ________ to ________
Sta ________ to ________

Date: Nov 16 2016
Rated By: IK/BN
#Utility Cuts: 0

FLEXIBLE PAVEMENT RATING FORM

DISTRESS	Distress Weight	Severity WT.			EXTENT WT.			STR	Deduct POINTS
		L	M	H	O	F	E		
RAVELING	10	X			X				1.5
BLEEDING	5								
PATCHING	5								
DEBONDING	5								
CRACK SEAL DEFICIENCY	5								
RUTTING	10	X				X		XX	2.4
SETTLEMENTS	0								
POTHOLES	10							XX	
WHEEL TRACK CRACKING	15		X			X		XX	7.35
BLOCK AND TRANSVERSE CRACKING	10		X			X			4.9
LONGITUDINAL CRACKING	5	X			X			XX	
EDGE CRACKING	10			X			X	XX	1
THERMAL CRACKING	10		X			X			4.9
								TOTAL	22.05
								SUM	10.75
								PCR	77.95

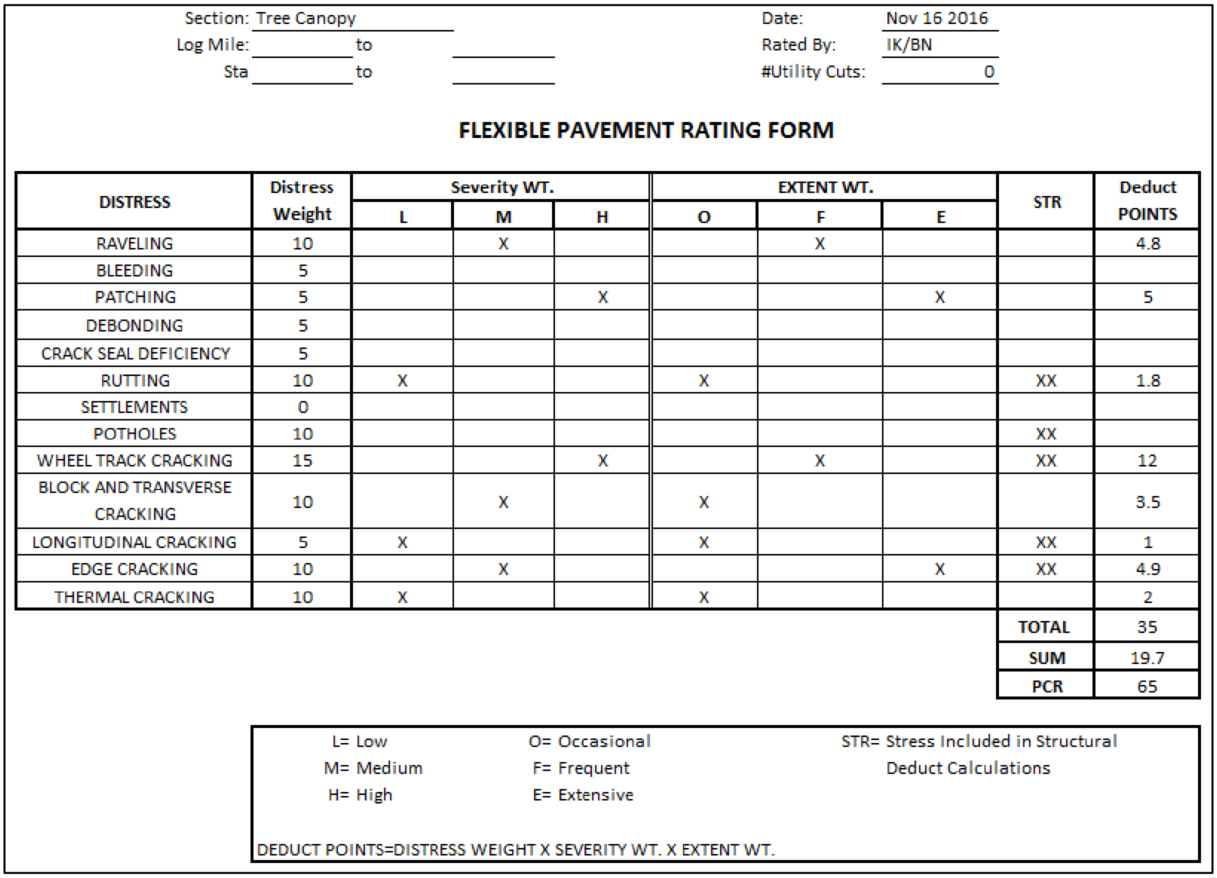
L= Low
M= Medium
H= High

O= Occasional
F= Frequent
E= Extensive

STR= Stress Included in Structural Deduct Calculations

DEDUCT POINTS=DISTRESS WEIGHT X SEVERITY WT. X EXTENT WT.

Table 3. ODOT PCR rating: canopy section (OH-356)



Section: Tree Canopy
Log Mile: ________ to ________
Sta ________ to ________

Date: Nov 16 2016
Rated By: IK/BN
#Utility Cuts: 0

FLEXIBLE PAVEMENT RATING FORM

DISTRESS	Distress Weight	Severity WT.			EXTENT WT.			STR	Deduct POINTS
		L	M	H	O	F	E		
RAVELING	10		X			X			4.8
BLEEDING	5								
PATCHING	5			X			X		5
DEBONDING	5								
CRACK SEAL DEFICIENCY	5								
RUTTING	10	X			X			XX	1.8
SETTLEMENTS	0								
POTHOLES	10							XX	
WHEEL TRACK CRACKING	15			X		X		XX	12
BLOCK AND TRANSVERSE CRACKING	10		X		X				3.5
LONGITUDINAL CRACKING	5	X			X			XX	1
EDGE CRACKING	10		X				X	XX	4.9
THERMAL CRACKING	10	X			X				2
								TOTAL	35
								SUM	19.7
								PCR	65

L= Low
M= Medium
H= High

O= Occasional
F= Frequent
E= Extensive

STR= Stress Included in Structural Deduct Calculations

DEDUCT POINTS=DISTRESS WEIGHT X SEVERITY WT. X EXTENT WT.

General Observations

Some of the general observations witnessed between the canopy versus exposed section of the roadway include:

(i) Effects of leaves on roadway

During the fall season, leaves from trees alongside the roadway had fallen off as seen in Figure 6(a) on OH-356. These fallen leaves, depending on roadside edge (slope/no-slope or shoulder size), have the potential of covering the edge lines (see Figure 6(b) on OH-124) of the roadway and this can become a safety concern especially during foggy, and wintery snow conditions when drivers have a reduced vision and use line markings to maintain their position on within the travelled lane. Also, the fallen leaves store moisture within their layers which could potentially freeze during the evenings (when temperatures drop during the winter) and form a layer of ice. This mix of leaves (coated with ice) can potentially be a safety concern for drivers

Figure 6. Effect of Fallen Leaves on Roadside.

who are unaware of the presence of the slick surface. Additionally, there can potentially be concerns of the fallen leaves blocking ditches, culverts and drop inlets.

(ii) Effects of moisture on pavement surface

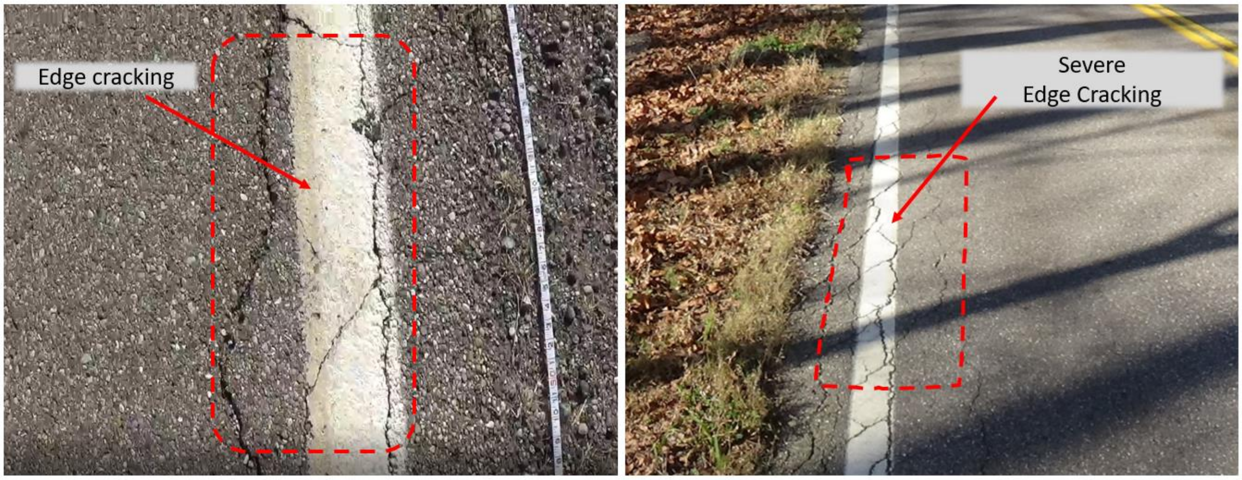
On the canopy section of roadway, there was noticeable amounts of raveling occurring on the pavement surface as shown in Figure 7. The observed stripping of aggregate particles and cracking is partially due to the presence of moisture on the pavement surface. It is likely that moisture is present for long periods due to a lack of exposure of the pavement to direct sunlight. It was also observed that within the canopy shaded sections, there were a number of locations that were patched (see Figure 8) due to localized raveling as opposed to unshaded sections that had no patching.

Additionally, the curved sections of the roadway had relatively more patching than on the straight sections. On one hand, it is likely that the curved sections are prone to raveling faster than straight sections because there is an increased amount of traction and braking going on between the tires and pavement on the curved sections. On the other hand, and from a safety perspective, this is a concern because (i) during the winter, the moisture present on the pavement could potentially freeze and cause the pavement surface to become slippery, and (ii) there is a high potential of hydroplaning.

Figure 7. Raveling on Canopy Covered Pavement Sections.

Figure 8. Patched Pavement Sections Under Canopy Cover.

There were also noticeable defects on the edges of the roadway as depicted in Figure 9. On the unshaded section of roadway, there was longitudinal cracking that is typical of conditions where the sub-surface of shoulder is weak as seen in Figure 9(a). However, on the canopy covered section, in addition to the cracking seen on the exposed roadway section there was also noticeable occurrence of severe edge cracking on the roadway as shown in Figure 9(b). It is believed that this edge cracking is a result of the pavement holding moisture much longer than sections which do not have canopy cover.



(a) Exposed section with Edge Cracking **(b) Canopy section with Severe Edge Cracking**

Figure 9. Pavement Surface Cracking Along Roadway Edges.

(iii) Effects on pavement condition

The section surveyed that did not have a tree canopy showed distress consistent with the flexible pavement type. Transverse thermal cracks were present. Longitudinal edge cracks along the edge of the pavement as well as some block and transverse cracking. Wheel track cracking was also observed. The section surveyed with the overhead tree canopy consisted of 2520 square feet of patched area, approximately 42% of the entire surveyed area. In the remainder of the area surveyed, sections that were not newly patched exhibited areas of low to medium severity raveling, medium severity edge cracking and low severity transverse cracking consistent as well as some block and transverse cracking and wheel track cracking. The PCR rating for the canopied section included the rating for the patching, although this would not normally be added since it constitutes a large portion of the section and thus would normally be rated as a new pavement. The survey team wanted to highlight the fact that the canopied section was recently repaired as opposed to the non-canopied section that was not repaired.

RESEARCH FINDINGS AND CONCLUSIONS

Literature Review

The literature on forest microclimate demonstrates that trees control the energy budget of the air and ground beneath them and substantially affects the accumulation and persistence of moisture, factors known to be relevant to pavement condition. Variation in air and ground temperature, humidity, and ground moisture under the canopy is dependent on species identity (reflected in canopy architecture) and the size and structure of individual trees. The range of variation observed in forests is easily noticeable to humans, and potentially sufficient to affect the properties of asphalt pavement.

Environmental effects, and especially climate, are the leading causes of pavement deterioration and failure. Pavement degradation by thermal cycling, aging, and moisture penetration all depend on exposure to the open sky – the source of solar radiation and precipitation – so it is reasonable to assume that tree canopies, which block the sky, would mitigate such damage. Shade reduces thermal loading, potentially reducing the tensile stress in the surface layer caused by repeated expansion and contraction. To the extent that pavement aging is caused by UV radiation and temperature, shade trees potentially delay aging and maintain tensile strength (Adlinge and Gupta 2010). Trees may protect pavement from moisture-related degradation by catching a substantial amount of precipitation on leaves and stem and discouraging condensation (dew) formation. A more stable microclimate under a tree potentially reduces freeze - thaw cycling and, thus, protects pavement. It is also possible that trees aggravate moisture-driven forms of degradation by delaying evaporation in the shade of the canopy. Undoubtedly all of these processes work simultaneously, but the relative importance of each in a real pavement situation remains to be determined.

Microclimatic effects observed in natural forests also apply to urban and suburban landscapes created by humans. Indeed, solar radiation produces more extreme heat variation in urban landscapes due to the peculiar thermal properties of pavement. Studies in urban settings consistently demonstrate the ability of tree canopies to control pavement temperature on a very fine spatial and temporal scale by regulating solar radiation. Tree canopies also intercept large amounts of rainfall when it arrives in small-moderate amounts. These observations confirm the climate generalizations from forests, and allow numerical values to be placed on variation in pavement temperature and moisture. Such variation appears to be more extreme in urban settings than in natural forests. However, these ranges of temperature and humidity are similar to ranges examined in studies of pavement performance, suggesting that tree shading is relevant to pavement condition and service life.

The effect of roadside trees on road safety is a complex topic involving pavement condition, driver perception, and positioning of obstacles. To the extent that roadside trees influence pavement condition, they affect driver behavior, and they also affect the quality of the driving surface and, hence, road safety. Roadway designers simply regard trees as hazards to be removed. However, recent work suggests an interaction of road layout and driver behavior such that tree collisions are concentrated on wide, straight, high-speed roads in rural areas. In urban and suburban areas, data actually shows fewer and less serious crashes in the presence of trees. This may be related to the slower driving speeds observed in the presence of trees.

Ohio and Other State DOT Practices

Most practitioners believe there is a definite interaction between tree canopy and the pavement surface underneath it. Whereas canopy is understood to be due to trees in close proximity to (alongside) the roadway, it is believed the orientation of the highway would also affect shading. That is, highways running predominantly in the east/west or north/south direction will tend to have predictable shading. There was an overarching belief among practitioners that shading from tree canopy caused varying surface/subsurface temperatures, affected the moisture (rain, snow/ice) levels, was responsible for falling debris, and caused distress on the pavement surface. It was believed the moisture is not necessarily from snow and rain events but also from condensation dripping from tree branches. Thus the tree concerns were not only for periods of time when the trees had their leaves (spring/summer) but also when the leaves were not present (fall/winter).

It is believed shaded road sections were either the first to freeze and/or last to thaw, in which case the roadway surface becomes slick and is a hazard to the travelling motorist. Trees were also associated to falling debris (fruits, leaves, branches) which posed a threat of road closures, fatal and/or injury crashes, difficult to see edge line markings in foggy conditions, and clogged drainages. The pavement was thought to experience accelerated degradation in shaded sections due to moisture remaining on the pavement for longer periods. Shaded sections were understood to become prone to thermal cracking (attributed mainly to a rapidly changing microclimate: freeze/thaw cycles) and therefore moisture will permeate down to the substructure and cause damage to the roadway in the form of potholes. Concerns associated to variations in compaction densities, differential setting of HMA overlays, and tree resins altering the chemical properties of the asphalt were also raised.

Tree canopy is observed to initiate increases in routine maintenance and labor costs. Shaded sections were observed to demand relatively higher amounts of salt and/or deicing agents during winter operations, required frequent resurfacing/patching/overlays, and required routine drainage maintenance – all of which necessitated additional labor and equipment. Additionally, in locations with a potential for increased fallen limbs, there was need for immediate clearing which required road closures and subsequently caused disruptions in traffic.

The general practice to mitigate/manage the tree canopy is to perform roadside tree removal, ground-to-sky trimming, and/or tree limb thinning along routes and/or roadway sections identified as demonstrating the effects associated to trees alongside the roadway. Practitioners take a conservative approach making the safety of drivers their highest priority and so the tree removal/trimming practices adopted are based on AASHTO guidelines of providing a “forgiving” roadside clear zone for errant vehicles. It should be noted here that, practitioners claim to be extremely considerate of protected species in their tree mitigation and follow federal guidance prepared by the U.S. Fish and Wildlife Service. Selection of routes/sections for mitigation are based purely on past experiences of county managers and calls received from the general public. For many of the practitioners, tree canopy issues are dealt with continually on a case-by-case basis. Only select practitioner’s mentioned their mitigation practices are prioritized on the basis of a defined monitoring program.

In spite of the reported adverse effects tree canopy can have on pavement, safety, and maintenance; there are those who advocate for having trees alongside the roadway. They reference to the positive benefits experienced with trees in urban locations (as referenced in the literature). It is believed that, roads with canopy do not pose any problems and the air moisture circulation caused by the tree canopy is probably a good reason for no negative impacts on the pavement surface. In fact, it was thought that driving through a canopy is a pleasant experience and it makes drivers go slower, is a good safety precaution, and develops happier neighborhoods. These advocates suggest planting specific tree species that are adaptable to the roadside, tolerant to the damage caused by salt from winter snow operations, and provide a scenic touch to the roadside.

Trees Canopy Findings/Issues

The findings of this research point to large bodies of published research on the microclimates around trees, on the response of pavement to microclimate, and on the influence of trees on urban climate which allow the effect of roadside trees on pavement degradation and road condition to be estimated indirectly. However, there is need to better understand the topic and henceforth provide informed guidance on mitigation and maintenance practices, some issues that were identified in this research need to be addressed. These include:

- There is little or no research providing any empirical or scientific evidence into the effects of tree canopy overtop or alongside the roadway. The literature is not very conclusive on the topic with the most definitive research being that performed by McPherson and Muchnick (2005). Practitioners also infer to an interaction citing adverse, and also, beneficial effects of tree canopy however, these are based on experiences and are mostly anecdotal.
- Currently, tree canopy issues are “fixed” by removing the trees and/or cutting back the trees. There are two concerns here:
    (i) There is no specific guidance or formal process on how selection of routes or roadway sections is performed. Currently, routes or roadway sections are selected based mainly on experience – reporting by county managers, and complaints from the public. And, where PCR is adopted, there is a bias in selection in that PCR is not significantly affected by the shaded sections.
    (ii) In locations where the tree canopy is removed, the claim is that it mitigates the adverse effects. Also, the decision to continue tree canopy trimming is driven purely by past experiences. However, these benefits are based on anecdotal

evidence and no empirically driven research studies are available in support. Without any empirically driven research showing the benefits, it is not possible to have a clear idea of the benefits versus costs and there could be challenges with cutting back the tree canopy (or tree removal). For example, with areas beside slopes/hillsides, where canopy is removed/cutback getting into protected lands, the pavement still remains completely shaded by the slope/hillside.

- Roadside tree maintenance is performed mainly by engineers who are lacking in their ability to identify trees, understand them, and know when to trim or not to trim. There is need for some kind of training from certified arborists or even including certified arborist(s) to give guidance to maintenance crews.
- Budget allocations are shared among many maintenance activities such as winter maintenance and roadside operations therefore canopy related maintenance is low priority. This has led to inconsistencies in keeping the canopy trimmed back and a major effort will be needed.

PHASE II: PLAN OF ACTION

On the recommendation of the technical panel, the Ohio University research team anticipate pursuing the recommendations that have been presented. The overall goal of phase II would be to provide ODOT with a better understanding of the effects of tree proximity on pavement integrity, drivable surface condition, and safety. The proposed design for the tree and pavement study to be adopted for phase II is depicted in Figure 10. Specifically, phase II will attempt to fill the gap in the body of knowledge on how trees influence pavement degradation and safety in a cool-temperate climatic region. Based on the findings from phase I, the research team propose to pursue the following testable predictions.

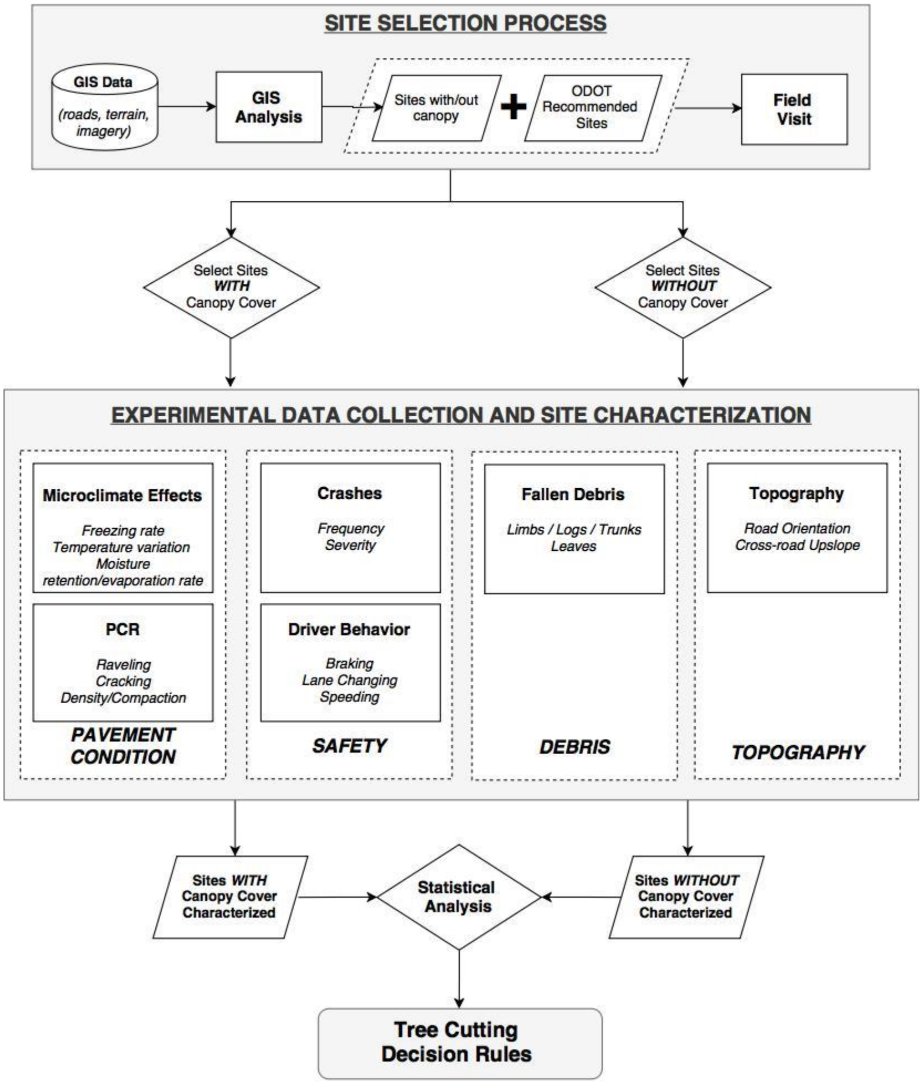


Figure 10. Proposed Study Design for Phase II.

Testable Predictions

1. Tree canopy alongside and overtop the roadway influences the construction process – placement of new pavement and also HMA overlays/patching/resurfacing. It is predicted that there will be differences in compaction density, existing surface condition, and differential setting between pavement under trees and in nearby open pavement sections. These differences are likely to affect the life expectancy of pavement overlays/patching/resurfacing.

2. Tree canopies act on pavement by moderating thermal cycling (the mechanism proposed by McPherson and Muchnik, 2005). In this case, there will possibly be less block and transverse cracking under trees.

3. Tree canopies affect pavement by catching moisture on their foliage, thereby reducing the amount of moisture reaching the pavement. We predict that pavement under trees has less alligator cracking in wheel tracks than pavement under an open sky, less debonding, and less fine-scale cracking throughout.

4. Where the moisture from rainfall does reach the pavement, tree canopy can reduce evaporation, thereby accelerating moisture damage and water infiltration in the pavement sub-structure. This would be supported by observation of serious edge cracking and debonding under trees than under an open sky. The research team predict there will be moisture-related differences in pavement deterioration between shaded pavements and open pavements.

5. Tree canopies act on pavement by absorbing soil moisture, thereby reducing the amount of moisture reaching the pavement from below. The research team predict less subsidence and expansion under trees than under an open sky.

6. If tree canopies cause pavement deterioration and in turn affect road safety, the research team predict that all measures of deterioration and safety will be proportional to the size, age, and canopy density of overhanging street trees.

7. If tree canopies influence pavement condition, then this will subsequently affect the comfort and safety of the roadway. The research team predict an increase in crashes caused by skidding on wet/icy pavements and also that there will be moisture-related differences in skid resistance between shaded pavements and open pavements.

Field Monitoring Plan

1. Selection of Study Sites.

The Ohio University research team will identify appropriate test locations for this study. At any given location, pavement test sections will be selected on the basis of available road data and tree cover information. Sections will be selected in ODOT districts 4, 5, 9, 10, 11, and 12 in two groups for a) individual-tree scale study focused on microclimate and individual tree features, and b) road section scale study focused on landscape variation and driver behavior. In both surveys, sections will be stratified by pavement age to control for background differences in maintenance and construction history.

a) At the individual-tree scale, the sections of pavement will be selected in pairs including one section under a dense tree canopy and another nearby section under an open sky allowing pairwise comparisons within pavement of the same mix and age. The size of a test section (approx. 1.5 meter x 1.5 meter [5 feet x 5 feet]) will be determined by the size of individual roadside trees. This pairwise approach will allow the research team to examine the effect of tree size, species, and canopy density on pavement condition with great precision – important information that comments on the value of tree management. Shaded pavement sections will have their center point directly opposite the trunk of an overhanging tree. The overhanging canopy must obscure at least 90% of the sky as viewed from the section center. Open-sky pavement sections will have no more than 5% canopy coverage. A third, partially shaded pavement section will be situated within the same pavement mix and age under 40-60% canopy coverage. This partially shaded plot allows conclusions about the value of pruning. Selection of all three pavement sections at a single location will ensure homogeneity in terms of age and composition of pavement material. All three pavement sections will be replicated 50 times to ensure statistical power in the subsequent analysis.

b) At the road scale, to study impact of tree canopy on road pavement condition, safety and maintenance, it is critical to set up a factorial experiment in which a few important factors are tested for their individual and combined effect on pavement and driving conditions. Because of the large study area and many possible conditions that maybe observed, it becomes necessary to rely on GIS based analysis to identify candidate sites where field experiments will be set up for testing different types of road-sections. For simplifying the scope of the field experiments, road-section survey sites will be selected along rural roads using GIS based analysis to test the impact of three factors (in order of importance) on pavement conditions.

i) *Presence of tree cover*: Given the research objectives of this project, the most important variable for road selection will be the presence or absence of trees near roads. For experimental control and comparison purposes, road sections will be classified as near (within 15-20 feet) and distant (200 feet or more) from trees. The tree cover analysis will be based on GIS based spatial analysis of categorically coded landcover datasets from the US National Land Cover Database (NLCD) and latest publicly available high resolution imagery.

ii) *Road orientation*: The second variable of interest is the orientation of the road, which affects road pavement exposure to sunlight (diurnally and annually). GIS-based directional analysis of road datasets available from ODOT will be used to identify two types of road-segments: those trending either (approximately) north-south (0° ± 15° azimuth) or east-west (90 ± 15° azimuth). Using two distinct road orientation categories will greatly simplify experimental design, but still provide sufficient sample size since roads in Ohio are known to trend along the four cardinal directions.

iii) *Cross-road terrain slope*: Another important factor that affects exposure to sunlight is cross-road terrain slope, which will be the third variable of interest for selecting road sections. Road sections surrounded by flat or down-sloping terrain will receive much more direct sunlight (assuming no tree cover and open sky conditions) than road-sections surrounded by sloping land on one or both sides. Thus, road sections will also be classified as passing through three types of sloping land: flat (0% - 2%), moderately up-sloping (2% - 5%, and steeply up-sloping (> 5%) on one or both sides. Terrain slope analysis will be done primarily using GIS based automated slope analysis and classification based on digital elevation data. However, because the research team expect certain limitations of using conventional GIS slope analysis tools for accurately classifying terrain into the three cross-road slope categories, visual analysis of topographic maps and 3-dimensional GIS displays will be needed for secondary verification and final selection of road segments.

iv) *Constant background factors*: While other factors (road width, speed limit, pavement age, road curvature) may also affect road safety conditions, adding more factors would greatly increase the number of sites required and the overall scope of the work plan. For such reasons, these factors will still be used in selecting road-sections, but only as "background control" factors that can be assumed to not vary much between all experimental sites. Based on current information, it is expected that the study will focus on road sections which are approximately 150 meters (500 feet) long, have two-lane widths, and characterized by low to medium road sinuosity (< 10° curvature) and paved between 10-15 years ago will be considered as potentially selectable for experimental analysis. GIS based road sinuosity analysis will be used to find road segments under screening of road conditions can be done efficiently only with GIS based parameterization and spatial analysis of road datasets for the study area.

Based on the above factors, data will be analyzed as a full factorial model with individual sub-sections nested within road stretches and traffic frequency included as a covariate. The complete experimental design will include:

2 tree proximity × 2 road orientations × 3 slopes × 5 replicates = 60 road sections.

2. Data Collection at Study Sites.

At each of the study locations (selected as described above), the research team will collect several types of data, as summarized in Figure 10, describing tree canopy, pavement condition and temperature variation, traffic loading, safety, and weather. Specific variables and proposed monitoring equipment are detailed below.

Traffic Data

24-hour traffic count and classification data will be collected at each test site using standard traffic data collection equipment available within the Civil Engineering department at Ohio University. Any archived traffic information available from ODOT will also be located and used.

Pavement Data

Data related to pavement construction and maintenance for the selected test locations will be obtained from ODOT archives. This will allow sites to be stratified by age in all analyses.

Additionally, pavement condition rating assessment will be conducted according to ODOT guidelines. Any kind of distress – transverse and edge cracking, raveling, and delamination, will be assessed following the standard protocols laid down in the Ohio Pavement Condition Rating Manual (PCR; Ohio DOT 2006). In addition to visual estimates, any pavement rutting will be quantified as the maximum difference in elevation within the length of a 4 foot (1.2-meter) straight-edge leveled within the pavement section. Surface roughness will also be quantified using the ORITE profiler and ProVAL software. Pavement condition data will be collected prior to the start of research activities and then continuously as the project progresses.

Pavement surface temperature variation data will also be collected over a minimum 48 hour period, during which IR or other temperature sensors will collect pavement surface and ambient temperature readings from the study locations. This data will be used to quantify the effect of the tree canopy.

Tree Canopy Data

Tree canopy over the pavement sections will be described in terms of tree diameter, height, health, foliage density, and species. Canopy density will be measured using image analysis of hemispherical canopy photos, a method widely used in forestry; other parameters will be assessed visually. These data will be used as the independent variables in all analysis of tree canopy and pavement integrity and surface condition.

Safety Data

In order to provide insight into the effect of tree canopy on pavement surface and its subsequent effect on highway safety (testable prediction 7 above), the research team will collect and analyze crash data from the selected sites. The team will take a detailed look at available police crash reports from ODOTs GIS Crash Analysis Tool (GCAT). One concern with crash data analysis is that crashes are random events and their occurrence is rare. To account for this potential limitation, the research team will make an effort to look at surrogate measures such as skidding, hard braking, and lane stability. These surrogate measures will be observed using video data and radar sensors.

Weather Data

The research team will collect weather-related data at the test locations. These data will assist in answering testable predictions 4, 6, and 7 (described above). Incident energy will be measured in terms of surface heating. The research team proposes using wireless temperature sensors and infrared imagery to develop temperature profiles of the pavement sections during each of the four seasons. Data collection duration will depend on current weather and site conditions. Data will be recorded on: snow accumulation, the rate at which snow melts away, the presence and level of ice on the pavement surface, and the skid resistance of the pavement surface. Snow and ice data will be collected in the winter as snowfall allows. The study locations will be monitored after precipitation events to determine the accumulation and persistence of snow and ice. Snow depth and areal cover will be measured at the cessation of a storm. Study locations will be revisited at intervals of 24, 48, and 72 hours to measure change in depth and coverage. Snow/ice retention and moisture persistence will be compared between shaded and unshaded sites, and compared with tree size and crown density, using generalized linear models as described below for pavement integrity and highway safety.

To assess standing water and evaporation in the individual-tree survey, water will be experimentally added to plots and surface wetness assessed at intervals. Because experimentally wetted sections will be very small (18 x 18 inches), because the amount of water is modest, and because the study would be conducted in mid-summer (i.e. no chance of freezing), we do not anticipate any safety issues. Preliminary trials show that standing water disappears within ca. 30 seconds, leaving only moist pavement.

3. Data Analysis.

A data driven analysis will be performed that will provide answers to questions including:

a) “Does pavement quality differ between shaded, partially shaded, and open-sky plots?”
b) “How does the effect of shading compare with effects of other factors which commonly contribute to pavement deterioration?”
c) “Do individual-tree observations scale up to highway management units?”
d) Does tree canopy cause changes to the pavement condition that can subsequently create hazards for drivers? If yes, then what factors specifically contribute to the crashes?

Using the individual-tree data, the three shading conditions will be compared for any rutting, raveling, and crack length, and for the PCR summary index using General Linear Models with pavement section as a blocking factor. All measures of pavement condition will be compared with shading condition, pavement age, traffic frequency, slope, incident light, and tree size using statistical methods including Partial Least Squares Regression, and other Multivariate Regression methods tolerant of collinearity among predictor variables. Individual variables will be “partialed” out and their contribution examined separately (Garthwaite 1994).

The examination of pavement condition and tree cover will be repeated at a coarser scale using the rural road data. Pavement condition measures will be analyzed as a General Linear Model considering slope, orientation, and tree proximity as factors. The analysis will be repeated with weather variables (i.e. snow depth, ice persistence, surface temperature, surface moisture, etc. as dependent variables to address the safety question.

A statistical analysis of the crash data will be performed to understand any potential relationships that may be present between tree canopy, pavement condition, and highway safety. The phase I findings indicate practitioners hypothesize that tree canopy affects pavement conditions (e.g. retained moisture that freezes and creates black ice) and as such adversely affects road safety. Additionally, there is no empirically driven analysis that suggests safety is improved once tree canopy is removed and/or trimmed. This highway safety motivated analysis will be undertaken in two parts. The first part will attempt to gain an understanding of the relationship between tree canopy and crashes (at all injury levels) by developing negative binomial generalized linear regression models. The negative binomial model is the accepted practice for traffic safety researchers given its ability to account for over dispersion (Washington, Karlaftis, and Mannering, 2010). The second part will attempt to predict any improvement(s) in safety by looking at crash data from before and after tree canopy removal/trimming. Methods described in the Highway Safety Manual (AASHTO, 2010) will be adopted.

4. GIS-Based Workflow Management

Since most of the data and experiments envisaged for this project have a strong spatial dimension, the research team will rely on a GIS based workflow for managing our data and supporting our decision-making processes. The research team anticipate GIS database management, mapping, and spatial analysis being critical for most Phase II tasks (site selection, data collection and analysis) outlined above. It is also expected GIS will be useful in statistical analysis and integrating results from different experiments to prepare our final recommendations and guidelines from this project. The research team will be using the industry standard ArcGIS 10.4/10.5 GIS software and Microsoft Excel software to implement our workflow model and for creating all our maps and reports for communicating results. At the end of Phase II, the research team will provide a clearly documented GIS-based workflow explicating all decision-making criteria for data acquisition, processing, mapping and spatial analysis, so that ODOT staff can use it for making effective operational decisions.

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APPENDIX A: INTERVIEW/SURVEY QUESTIONNAIRE

Note: Recruitment e-mail requesting participation in interview will be sent via e-mail to contacts at the following state Departments of Transportation: District of Columbia, Illinois, Indiana, Kentucky, Maryland, Michigan, New York, Pennsylvania, Virginia, West Virginia, and Wisconsin. Recruitment e-mail will be customized as noted in italics.

Recruitment E-Mail

Dear <*Name of Contact*>:

Ohio University, in conjunction with the Research and Development Office at the Ohio Department of Transportation, are conducting a research study examining state DOT policies and practices with regards to the effects of tree canopy alongside and overtop roadways. The <*Name of State DOT Agency*> has been selected on the premise that it experiences similar climatic conditions - relatively similar rainfall, average temperatures, and extreme temperature differentials - to those in Ohio. You are receiving this message because we identified you as an individual who would be able to provide us with the information on practices in <*state*>.

Request: We want to schedule an interview with you and/or your colleagues to learn more about the methods used by the <*Name of State DOT*> for addressing tree canopy alongside and overtop your roadways. The interview will be conducted via telephone and will take 20-30 minutes. You are welcome to include other colleagues in the interview if you wish.

If you feel that you are not the correct individual for this request, please contact me (see contact information below) and forward our message to the correct individual in your organization. Your participation in this research study is voluntary and your responses will be kept in strict confidence. We are only interested in your state DOT’s practices and the research team will not identify you by name in any published reports.

We greatly appreciate your help and thank you for your time and efforts on our behalf and for your willingness to discuss with us your state’s practices on this topic and we look forward to speaking with you. If you have any questions regarding this research study, please contact me at 740.593.4151 or via email at naik@ohio.edu.

Sincerely,

Bhaven Naik, Ph.D., P.E., PTOE.
Principal Investigator
Department of Civil Engineering
Ohio University

This research study has been reviewed by the Office of Research Compliance, Human Subjects' Protection Program and/or the Institutional Review Board at Ohio University. For research-related problems or questions regarding your rights as a research participant, you may contact these offices at 740.593.0664 or compliance@ohio.edu.

Note: The "Interview Framework" described below is a general outline of questions and topics for discussion during the telephone interview. The framework is designed to obtain the desired information but also be flexible to pursue interesting items that come up during the conversation. Framework will be customized as noted in italics.

Interview Framework

Introductory Script:

Thank you very much for taking time to talk with us today about this important topic. Your input will be valuable for this research study. We know that your time is valuable, so we have prepared a list of questions that will allow us to complete this interview during our scheduled time of 30 minutes or less.

First, we would like to understand more about how your roadway maintenance and/or roadside maintenance programs are organized.

- Which specific division(s) is involved with maintenance and upkeep of the roadway surface/roadside (i.e., pavement and right-of-way) in your agency? Are there any agencies outside the DOT that are involved with roadside maintenance and upkeep? If so, how are the responsibilities divided among the different agencies?
- How many employees in your division are involved with the maintenance and upkeep of the pavement and/or right-of-way?

Next, we would like to talk about your agency's standpoint on the effects that tree canopies may/may not have on the roadway surface and the drivers.

- Is your agency aware of any effects that tree canopy alongside and overtop the roadway may have? Is this something that is of concern to your agency? Are there any safety related concerns? Are there any pavement condition related concerns? Are there any maintenance related concerns? Are you aware of any comments/suggestions/concerns expressed by drivers that relate to tree canopy alongside and overtop the roadway?
- Are there any measures or practices in place that your agency has adopted to mitigate/manage these effects from tree canopy? If any, would you please elaborate on these? Are these practices driven by research studies? Or are these practices based on "feelings" or "assumptions" of what should be done to address tree canopy?
- Does your agency have public or private groups (such as scenic byways groups, conservation groups, local business and economic groups, tourism initiatives, historic perseveration, etc.) who have a vested interest in canopy covered/tree-lined roads? And if so, how are their concerns incorporated into the decision to manage tree canopy?

- Does your agency have protected species concerns as it relates to tree canopy removal (bats, migratory birds, etc.)? If so how does your agency manage those issues?

Next, we would like to talk specifically about the programs/practices your agency has in place to address the effects of tree canopy alongside and overtop the roadway.

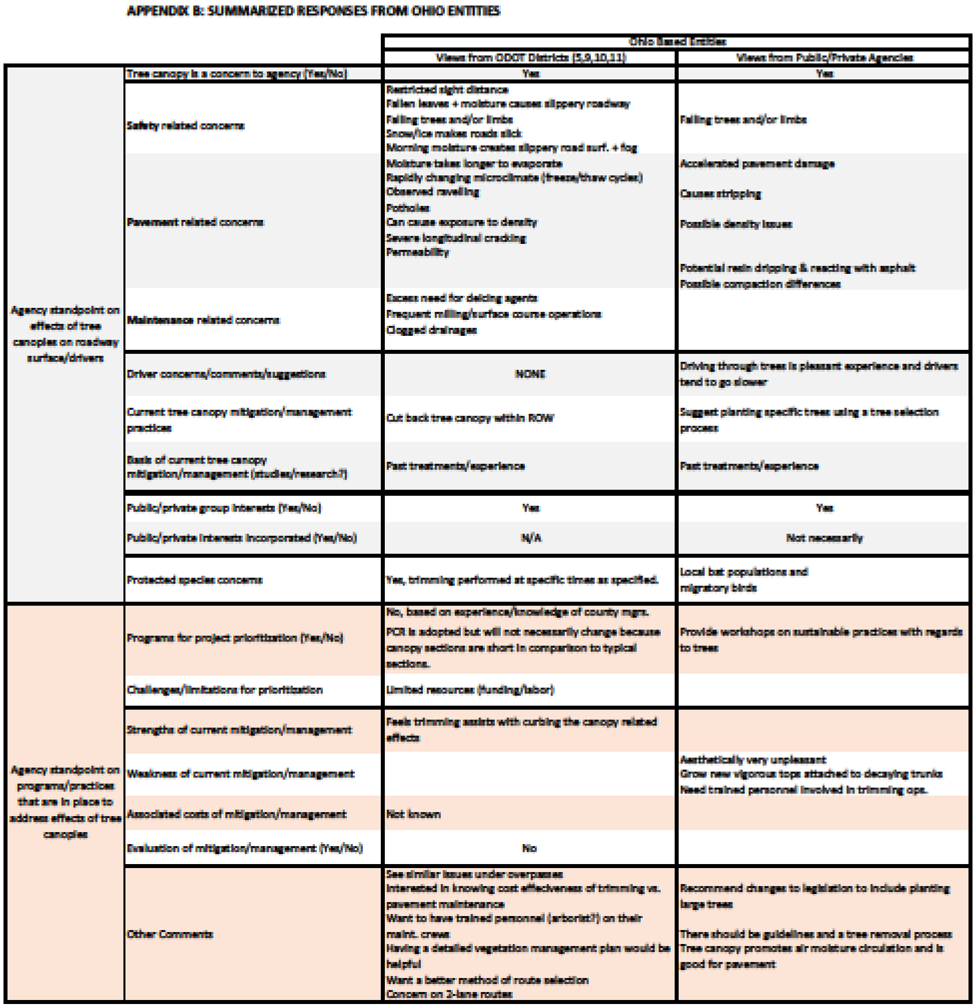
- If there is any program(s) that addresses specifically the issue of tree canopy, how are projects identified (or prioritized) for adoption of any practices? Is this a continuous or periodic process?
- What challenges or limitations does your agency face when prioritizing projects?
- In your agency's experience, what are the strengths and weaknesses of the practices you have in place to manage tree canopy?
- What are the costs associated with your tree canopy management practices?
- Has your agency performed any specific evaluations that target tree canopy management practices that you may have in place?
- Do you have a hazardous trees assessment process? If so, what program is your process based on?

That concludes our list of questions for this interview. Is there anything else that you would like to discuss that you think might be useful for our research study?

- Additional Discussion

Thank you for your time and for your input to this research study.

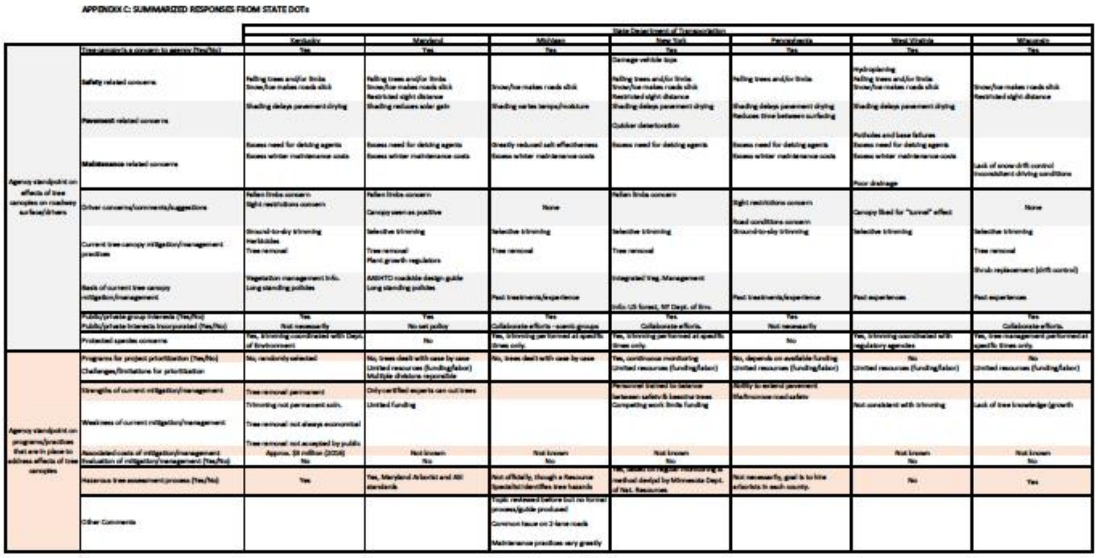
APPENDIX B: SUMMARIZED RESPONSES FROM OHIO ENTITIES



APPENDIX B: SUMMARIZED RESPONSES FROM OHIO ENTITIES

		Ohio Based Entities	
		Views from ODOT Districts (5,9,10,11)	Views from Public/Private Agencies
Agency standpoint on effects of tree canopies on roadway surface/drivers	Tree canopy is a concern to agency (Yes/No)	Yes	Yes
	Safety related concerns	Restricted sight distance Fallen leaves + moisture causes slippery roadway Falling trees and/or limbs Snow/ice makes roads slick Morning moisture creates slippery road surf. + fog	Falling trees and/or limbs
	Pavement related concerns	Moisture takes longer to evaporate Rapidly changing microclimate (freeze/thaw cycles) Observed ravelling Potholes Can cause exposure to density Severe longitudinal cracking Permeability	Accelerated pavement damage Causes stripping Possible density issues Potential resin dripping & reacting with asphalt Possible compaction differences
	Maintenance related concerns	Excess need for deicing agents Frequent milling/surface course operations Clogged drainages	
	Driver concerns/comments/suggestions	NONE	Driving through trees is pleasant experience and drivers tend to go slower
	Current tree canopy mitigation/management practices	Cut back tree canopy within ROW	Suggest planting specific trees using a tree selection process
	Basis of current tree canopy mitigation/management (studies/research?)	Past treatments/experience	Past treatments/experience
	Public/private group interests (Yes/No)	Yes	Yes
	Public/private interests incorporated (Yes/No)	N/A	Not necessarily
	Protected species concerns	Yes, trimming performed at specific times as specified.	Local bat populations and migratory birds
Agency standpoint on programs/practices that are in place to address effects of tree canopies	Programs for project prioritization (Yes/No)	No, based on experience/knowledge of county mgrs. PCR is adopted but will not necessarily change because canopy sections are short in comparison to typical sections.	Provide workshops on sustainable practices with regards to trees
	Challenges/limitations for prioritization	Limited resources (funding/labor)	
	Strengths of current mitigation/management	Feels trimming assists with curbing the canopy related effects	
	Weakness of current mitigation/management		Aesthetically very unpleasant Grow new vigorous tops attached to decaying trunks Need trained personnel involved in trimming ops.
	Associated costs of mitigation/management	Not known	
	Evaluation of mitigation/management (Yes/No)	No	
	Other Comments	See similar issues under overpasses Interested in knowing cost effectiveness of trimming vs. pavement maintenance Want to have trained personnel (arborist?) on their maint. crews Having a detailed vegetation management plan would be helpful Want a better method of route selection Concern on 2-lane routes	Recommend changes to legislation to include planting large trees There should be guidelines and a tree removal process Tree canopy promotes air moisture circulation and is good for pavement

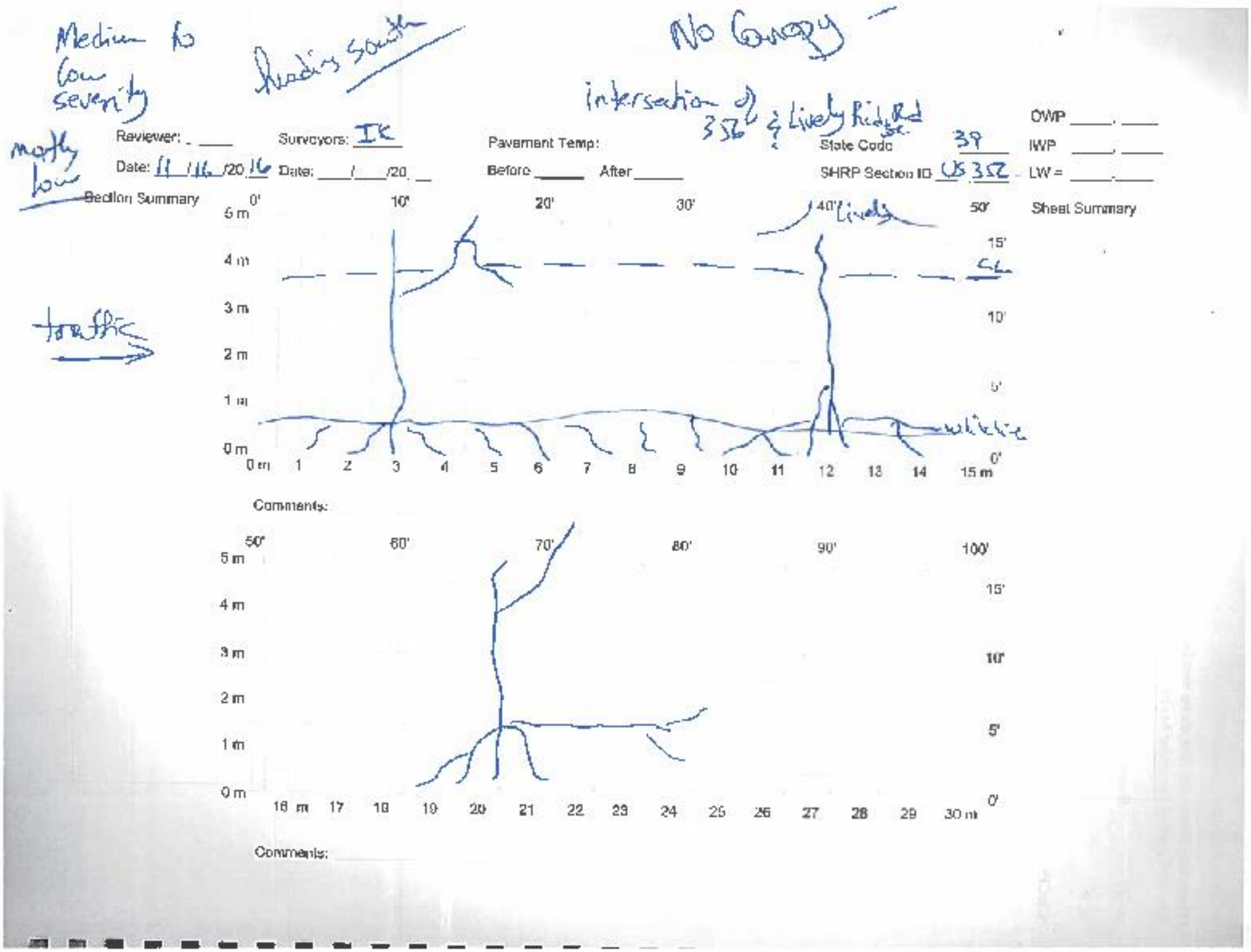
APPENDIX C: SUMMARIZED RESPONSES FROM STATE DOTs



APPENDIX C: SUMMARIZED RESPONSES FROM STATE DOTs

		State Department of Transportation						
		Kentucky	Maryland	Michigan	New York	Pennsylvania	West Virginia	Wisconsin
Agency standpoint on effects of tree canopies on roadway surface/drivers	Tree canopy is a concern to agency (Yes/No)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Safety related concerns	Falling trees and/or limbs Snow/ice makes roads slick	Falling trees and/or limbs Snow/ice makes roads slick Restricted sight distance	Snow/ice makes roads slick	Damage vehicle tops Falling trees and/or limbs Snow/ice makes roads slick Restricted sight distance	Falling trees and/or limbs	Hydroplaning Falling trees and/or limbs Snow/ice makes roads slick	Snow/ice makes roads slick Restricted sight distance
	Pavement related concerns	Shading delays pavement drying	Shading reduces solar gain	Shading varies temps/moisture	Shading delays pavement drying Quicker deterioration	Shading delays pavement drying Reduces time between surfacing	Shading delays pavement drying Potholes and base failures	
	Maintenance related concerns	Excess need for deicing agents Excess winter maintenance costs	Excess need for deicing agents Excess winter maintenance costs	Greatly reduced salt effectiveness Excess winter maintenance costs	Excess need for deicing agents	Excess need for deicing agents Excess winter maintenance costs	Excess need for deicing agents Excess winter maintenance costs Poor drainage	Lack of snow drift control Inconsistent driving conditions
	Driver concerns/comments/suggestions	Fallen limbs concern Sight restrictions concern	Fallen limbs concern Canopy seen as positive	None	Fallen limbs concern	Sight restrictions concern Road conditions concern	Canopy liked for "tunnel" effect	None
	Current tree canopy mitigation/management practices	Ground-to-sky trimming Herbicides Tree removal	Selective trimming Tree removal Plant growth regulators	Selective trimming Tree removal	Selective trimming Tree removal	Ground-to-sky trimming	Selective trimming	Selective trimming Tree removal Shrub replacement (drift control)
	Basis of current tree canopy mitigation/management	Vegetation management info. Long standing policies	AASHTO roadside design guide Long standing policies	Past treatments/experience	Integrated Veg. Management Info: US forest, NY Dept. of Env.	Past treatments/experience	Past experiences	Past experiences
	Public/private group interests (Yes/No)	Yes	Yes	Yes	Yes	Yes		Yes
	Public/private interests incorporated (Yes/No)	Not necessarily	No set policy	Collaborate efforts - scenic groups	Collaborate efforts.	Not necessarily		Collaborate efforts.
	Protected species concerns	Yes, trimming coordinated with Dept. of Environment	No	Yes, trimming performed at specific times only.	Yes, trimming performed at specific times only.	No	Yes, trimming coordinated with regulatory agencies	Yes, tree management performed at specific times only.
Agency standpoint on programs/practices that are in place to address effects of tree canopies	Programs for project prioritization (Yes/No)	No, randomly selected	No, trees dealt with case by case	No, trees dealt with case by case	Yes, continuous monitoring	No, depends on available funding	No	No
	Challenges/limitations for prioritization		Limited resources (funding/labor) Multiple divisions responsible		Limited resources (funding/labor)	Limited resources (funding/labor)	Limited resources (funding/labor)	Limited resources (funding/labor)
	Strengths of current mitigation/management	Tree removal permanent	Only certified experts can cut trees		Personnel trained to balance between safety & beautiful trees	Ability to extend pavement life/improve road safety		
	Weakness of current mitigation/management	Trimming not permanent soln. Tree removal not always economical Tree removal not accepted by public	Limited funding		Competing work limits funding		Not consistent with trimming	Lack of tree knowledge (growth
	Associated costs of mitigation/management	Approx. $9 million (2016)	Not known	Not known	Not known		Not known	Not known
	Evaluation of mitigation/management (Yes/No)	No	No	No	No		No	No
	Hazardous tree assessment process (Yes/No)	Yes	Yes, Maryland Arborist and ANSI standards	Not officially, though a Resource Specialist identifies tree hazards	Yes, based on regular monitoring & method devlpd by Minnesota Dept. of Nat. Resources	Not necessarily, goal is to hire arborists in each county.	No	Yes
	Other Comments			Topic reviewed before but no formal process/guide produced Common issue on 2-lane roads Maintenance practices vary greatly				

APPENDIX D: FHWA LTPP FIELD DISTRESS NOTES



Medium to low severity

heading south

No Canopy

intersection of 356 & Lively Ridge Rd

mostly low

Reviewer: ____

Date: 11 / 16 /20 16

Surveyors: IK

Date: ___/___/20__

Pavement Temp:

Before _____ After _____

State Code 39

SHRP Section ID US 352

OWP ____.____

IWP ____.____

LW = ____.____

Section Summary

Sheet Summary

Comments:

Comments:

ORITE • 151 Stocker Center • Athens, Ohio 45701-2979 • 740-593-1470
Fax: 740-593-0625 • orite@ohio.edu • http://www.ohio.edu/orite/