

Urbanization and Ecological Repercussion on Active Transport and Micromobility Facilities

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Abstract

The escalating impacts of ecological shifts present serious challenges to non-motorized transportation (walking, bicycling) facilities (NMTFs) and micromobility in Delaware. This study examines how coastal flow, temperature, flooding, and urbanization affect the accessibility, safety, and resilience of active transportation systems, using Delaware as a case study through geospatial analysis and demographic overlays. GIS-based mapping was applied to evaluate exposure of transportation infrastructure under coastal flow scenarios ranging from 1 to 7 feet, revealing that several NMTF corridors intersect with high-risk flood zones, posing threats to long-term usability. Projected temperature increases of 2.5 - 4.5°F by 2050 may promote active transportation during moderate conditions but also disrupt usage through infrastructure strain, health risks, and service interruptions. Flooding further damages critical infrastructure, while urbanization compounds these risks by increasing impervious surfaces, reducing natural drainage, and concentrating populations in vulnerable areas. Spatial analysis highlights significant overlaps between areas of high ecological exposure and communities reliant on walking, biking, and micromobility, underscoring the urgency of integrating adaptive infrastructure such as shaded pathways, elevated bike lanes, and flood-resilient surfaces into transportation planning. Expanding micromobility networks, enhancing cooling strategies, and prioritizing adaptive policies can mitigate ecological impacts on mobility and public health, contributing to more inclusive and sustainable environments. The findings highlight the need for resilient active transportation planning in areas facing ecological pressures. Future work may expand the analysis by incorporating community-based surveys and analytical tools to evaluate user experiences under changing environmental conditions.

Keywords

Active Transportation, Ecological Shifts, Micromobility, Sustainable Transportation, Transportation Facilities

1. Introduction

Active transportation, including walking, bicycling, and micromobility, is a rapidly expanding component of modern urban mobility systems [1]. Micromobility includes small, lightweight vehicles such as bicycles, e-bikes, and electric scooters that are typically used for short-distance travel. These modes of transportation are increasingly recognized for their potential to reduce congestion, lower emissions, and promote resilient urban transport solutions. The integration of Mobility-as-a-Service (MaaS) platforms is further facilitating access to shared transportation by combining public transit, bike-sharing, and car-sharing into unified, user-friendly systems [2]. Although this study focuses primarily on trails and active transportation corridors, micromobility facilities share similar vulnerabilities including exposure of charging stations, device durability issues during flooding, and operational disruptions under extreme heat.

Internationally, the transition toward electric micromobility is accelerating. Cities such as Kelowna, Canada, have implemented large-scale shared e-scooter programs, resulting in over a million rides and measurable reductions in car usage. Electric bikes, though they comprise a relatively small portion of total bicycles, account for a disproportionately large share of trips, highlighting their growing influence. In the United States, micromobility is gaining popularity in dense urban environments, where demand for cycling infrastructure and pedestrian pathways is rising. Cities like New York and San Francisco are leading efforts to incorporate shared micromobility options into the broader transportation landscape [3].

Despite growing adoption, several challenges remain. Investment in safe, dedicated infrastructures such as protected bike lanes, secure parking, and reliable charging stations is critical for continued growth. There is also a growing need for improved data collection to better understand usage patterns and support informed planning. At the policy level, regulatory frameworks have been developed in several cities to address speed limits, vehicle parking, and safety protocols. These regulations aim to reduce accident risks and improve the user experience by ensuring proper infrastructure is in place [4].

From an ecological standpoint, micromobility offers meaningful benefits by replacing short car trips and reducing vehicle emissions. Studies have shown that widespread use of electric scooters and shared bicycles can help alleviate urban congestion and improve air quality. However, realizing these benefits requires attention to lifecycle emissions and proper management of battery disposal and vehicle waste. Infrastructure planning plays a critical role in maximizing these gains. Urban areas that incorporate micromobility-friendly designs often see improved connectivity and reduced strain on conventional transportation systems.

In Delaware, cities such as Wilmington and Dover are taking steps to expand micromobility access and improve cycling infrastructure. These efforts align with broader strategies aimed at enhancing transportation resilience in the face of ecological shifts, including coastal flow, temperature increases, flooding, and urban-

ization. Technological innovations such as GPS integration, mobile apps, and dockless vehicle systems are helping make micromobility more efficient and accessible across diverse settings.

In addition to its transportation function, micromobility contributes to public health by encouraging physical activity and offering alternatives to car travel. As these systems continue to evolve, they are becoming a foundational element in sustainable urban development. With continued investment in infrastructure, technology, and planning, micromobility and active transportation can play a key role in building resilient cities that are better equipped to adapt to ongoing ecological shifts.

1.1. Coastal Flow

Human activities have significantly contributed to greenhouse gas emissions, leading to observable ecological shifts, including a change in global temperatures, approximately 0.2°C per decade according to the Intergovernmental Panel on Ecological Shifts. In response, there is growing emphasis on mitigation strategies that reduce emissions while promoting sustainable urban development. Among these, non-motorized transportation, such as walking and cycling, has gained attention not only for its environmental benefits but also for its potential to improve urban health, safety, and mobility.

Ecological shifts pose increasing threats to transportation infrastructure, particularly in low-lying and coastal areas [5]. Coastal flows, intensified storm surges, and more flooding events are of particular concern, as they can disrupt mobility networks and degrade infrastructure performance. Non-motorized transportation facilities, such as trails and bike routes, are especially vulnerable due to their surface exposure and proximity to natural features.

This study focuses on evaluating the vulnerability of trails and bike routes to projected coastal flow scenarios using Geographic Information System (GIS)-based analysis. By estimating potential flow extents and depths under multiple projections, this work aims to support proactive planning and inform infrastructure adaptation strategies in the context of ongoing ecological shifts.

1.2. Temperature

Global temperature trends continue to reflect the intensifying impacts of ecological shifts driven by human activities, including greenhouse gas emissions [6]. The summer of 2024 marked the hottest on record, with a global-average surface air temperature anomaly of +0.69°C above the 1991-2020 baseline for the June–August period, surpassing the previous record set in 2023. From June 2023 to May 2024, each month consecutively broke previous high-temperature records, underscoring the accelerating pace of ecological changes. In addition, global sea surface temperatures remained abnormally high, with August 2024 recording the second-highest sea surface temperature for that month according to data from NASA and the Copernicus Ecological Shifts Service.

In the United States, the rise in average temperatures has outpaced the global trend. Since 1895, the annual average temperature across the country has changed by approximately 1.3°F to 1.9°F, with most of this change occurring since 1970. The summer of 2024 was marked by more severe and widespread heatwaves, setting new temperature records in multiple regions. These extreme heat events have been accompanied by an increased frequency of related environmental stresses, including droughts and wildfires, which further underscore the pressing need for mitigation and adaptation strategies.

Delaware has experienced a similar pattern of rising temperatures, with the state's average annual temperature increasing by around 2°F since the early 20th century. This trend is consistent with broader patterns observed throughout the northeastern United States. Delaware is now facing more frequent and intense heatwaves, which impact multiple sectors, including health, agriculture, infrastructure, and energy systems. Projections indicate that the warming trend will continue, with elevated risks for coastal and urban areas due to heat stress and associated environmental pressures. These changes highlight the need for robust planning and infrastructure adaptation to maintain resilience in the face of ongoing ecological shifts.

1.3. Flooding

Flooding is becoming increasingly intense worldwide because of ecological shifts [7]. Projections indicate that overall flooding could increase by 9% to 49% by the end of the century, depending on ecological scenarios. Coastal flooding poses a particularly severe challenge, with forecasts suggesting a potential rise of up to 99% under lower-impact scenarios and up to 287% under higher-impact scenarios by 2100. Regions such as tropical Africa, parts of Asia, and global coastal zones are expected to face substantial increases in flood hazards. Shifting global precipitation patterns are a major driver of this trend, with many areas observing a 7% to 10% increase in heavy rainfall events, which significantly contributes to flood risk.

In the United States, flooding represents the costliest category of natural disasters. Between 1996 and 2023, approximately 70% of flood-related disasters were attributed to heavy rainfall, which is becoming more frequent due to ecological changes. Coastal areas along the Gulf and Atlantic coast are especially affected by rising flood levels. Nationally, average precipitation has increased by about 10% since the early 20th century, though this change varies regionally. The northeastern U.S. has seen the most significant rise in heavy precipitation events, whereas the Southwest has experienced more prolonged dry spells.

Delaware is especially susceptible to coastal flooding because of its low elevation and coastal geography. Over the past 30 years, the state has observed a 20% increase in the frequency of flood events. When combined with episodes of heavy rainfall, these floods place considerable stress on transportation systems, buildings, and other infrastructure. Delaware has also recorded an upward trend in an-

nual precipitation, with heavy rainfall events becoming 20% more common since the 1990s. This change elevates the risk of localized flooding, particularly in urban areas with limited drainage capacity. These conditions highlight the importance of long-term planning and infrastructure improvements to manage flood-related challenges linked to ecological shifts.

1.4. Urbanization

Urbanization is a defining global trend with far-reaching implications for ecological systems, infrastructure planning, and transportation development. As of 2023, over 57% of the world's population lives in urban areas, a figure projected to increase to 64% by 2040 and 68% by 2050. This expansion is shaped by rural-to-urban migration, economic opportunities, and population growth, particularly in developing regions. In contrast, developed regions such as North America and Europe are experiencing slower urban growth, with more emphasis on optimizing existing urban systems [8].

Urban areas are key drivers of global economic activity, but they also present challenges such as overcrowding, infrastructure strain, resource depletion, and ecological pressures. To address these, many cities are adopting smart technologies including artificial intelligence (AI), the Internet of Things (IoT), and data-driven urban planning, to improve transportation, infrastructure management, and overall resiliency. For instance, cities like Barcelona have successfully implemented digital solutions to enhance urban living through integrated mobility systems, efficient energy use, and responsive public services.

Sustainability and resiliency are becoming central pillars of urban planning. Cities are increasingly investing in renewable energy, energy-efficient buildings, and infrastructure that can adapt to ongoing ecological shifts. Given that urban areas account for approximately 60% of global greenhouse gas emissions, these efforts are essential to reducing environmental impacts while improving livability.

In the United States, approximately 83% of the population resides in urban areas, making it one of the most urbanized countries globally. Major metropolitan areas such as New York, Los Angeles, and Chicago lead in both population size and economic output. At the same time, mid-sized cities like Austin and Raleigh are experiencing rapid growth driven by factors such as access to services, employment, and urban amenities. However, urban expansion, particularly low-density development or sprawl, can lead to increased infrastructure demands and ecological stress, including higher emissions, habitat disruption, and flooding.

Cities across the U.S. are implementing policies that promote renewable energy adoption, green infrastructure, and more compact urban development to reduce these ecological pressures. Cities such as San Francisco and Portland are at the forefront of integrating public transit with pedestrian and micromobility infrastructure to support sustainable urban growth.

In Delaware, over 80% of the population lives in urban areas, placing the state among the most urbanized in the country. Urban growth continues through mi-

gration and economic development, particularly around cities such as Wilmington, Dover, and Newark. Wilmington functions as a key economic and administrative hub, while suburban expansion contributes to regional urbanization. This growth brings challenges such as infrastructure strain, land use pressure, and increased flooding risk in low-lying developed areas.

To manage the ecological implications of urbanization, Delaware is actively working to integrate green infrastructure, improve public transportation, and expand micromobility and pedestrian-friendly networks. These efforts support the state's broader strategy to build resilience in response to ecological shifts while maintaining urban functionality and efficiency.

2. Coastal Flow

This section also describes the methodological steps used in the geospatial analysis. Coastal flow is increasingly recognized as one of the most direct and visible consequences of long-term ecological shifts. Global monitoring over the past century shows a marked acceleration in the rate of coastal water level increase, with recent decades experiencing faster changes than any time in the 20th century. This trend is driven by a combination of thermal expansion, glacial melt, and the degradation of natural coastal buffers such as wetlands and ice shelves. While the magnitude and timing of future flow remain dependent on ecological scenarios, current projections indicate that coastal water levels may increase by 0.25 to 0.5 meters by 2050 and potentially exceed 1 meter by the end of the century. These changes present a profound challenge to transportation infrastructure in coastal regions.

The effects of coastal flow extend far beyond occasional storm-related flooding. In many low-lying areas, even modest increases in baseline water levels can result in more frequent "sunny days" or high-tide flooding, which occurs in the absence of storms. As coastlines become more regularly submerged, transportation facilities designed for dry-ground operations such as roads, sidewalks, trails, and bike routes, face chronic disruptions. The structural integrity of pavements is compromised when repeatedly exposed to saltwater, and the presence of standing water increases wear and shortens the lifespan of infrastructure. Drainage systems, which were originally engineered for historic conditions, often become overwhelmed, especially in urbanized coastal zones where impervious surfaces dominate.

Active transportation facilities are particularly vulnerable in this context. Trails and bike lanes are often constructed along scenic or environmentally sensitive corridors such as waterfronts, riverbanks, and converted railways that place them directly in harm's way. These areas, while attractive for recreation and mobility, are also some of the first to experience flow during high tides or storm surges. Flow reduces the usability of these facilities not only by direct submersion but also through erosion, sedimentation, and the accumulation of debris, which can make them unsafe or impassable. Even intermittent flooding events can discourage use,

reduce reliability, and lead to long-term deterioration if not properly maintained.

In addition to the physical risks, coastal flow also undermines the connectivity and continuity of non-motorized transportation networks. When a key segment of a trail or bike path is rendered unusable, whether temporarily or permanently, it can sever access to schools, workplaces, transit stations, or recreational destinations. This is particularly problematic in communities that have invested in integrated mobility systems where the biking and walking infrastructure serves as a crucial “last mile” connection to bus or rail services. The loss of such connections may force users to revert to motorized modes, increasing emissions and congestion, and reducing the attractiveness of active transportation overall.

The long-term consequences of coastal flow also complicate infrastructure planning and investment. Municipalities and transportation agencies must now consider not only current flooding risks but also evolving projections that span decades. Designing resilience involves trade-offs between elevation, material choice, drainage design, and long-term maintenance. In some cases, trails and bike routes may need to be relocated entirely to higher ground. In others, they can be retrofitted with elevated boardwalks, permeable pavements, or water-tolerant vegetation buffers. These adaptation strategies often come with significant cost implications, especially when applied across entire networks, and their effectiveness may vary based on local topography and hydrology.

This research presents a GIS-based model designed to evaluate how coastal flows as an ecological shift could affect non-motorized and micromobility transportation facilities in Delaware, particularly trails and bike routes. The model integrates spatial inventories of these facilities with three flow scenarios provided by NOAA. Using ArcMap’s intersection tool, the analysis identifies which portions of the network intersect with projected flow zones.

Each facility is assessed individually. Two key factors are analyzed: (1) the length of trail or route projected to be submerged, and (2) the maximum depth of flow on those segments. These two measures are used to assign a vulnerability rank to each facility. Routes with short impacted sections and shallow depths are considered more resilient and may require only minor, cost-effective adaptations. In contrast, facilities with longer submerged segments and deeper water levels are flagged as highly vulnerable and likely to require major investment to preserve.

The primary objective is to determine the vulnerability of active transportation corridors under low, medium, and high scenarios of coastal flow. The outcome of the analysis is a level-of-service (LOS) classification, ranging from A to F, assigned to each facility. This classification depends on the degree of flow and depth, helping to inform decisions about maintenance feasibility and long-term usability.

These insights provide a decision-support tool for transportation authorities such as the State DOT. For instance, a trail rated as LOS-F may be recommended for decommissioning, with resources redirected toward creating a new facility in a safer, less exposed location. This strategic planning helps improve resiliency across the active transportation network in response to future eco-

logical shifts (**Table 1**).

Table 1. Level of service estimation based on depth of water and length of flow for three coastal flow scenarios [9].

		Inundation Distance (%)						
		0 - 10	10 - 30	30 - 50	50 - 70	70 - 90	90 - 100	
Low (2ft)	Max Depth of Water less than 1 ft	LOS A	LOS A	LOS B	LOS D	LOS E	Out of Service	
	Max Depth of Water more than 1 ft	LOS A	LOS B	LOS C	LOS D	LOS f	Out of Service	
Medium (4ft)	Max Depth of Water less than 2 ft	LOS A	LOS B	LOS D	LOS E	LOS F	Out of Service	
	Max Depth of Water more than 2 ft	LOS B	LOS C	LOS D	LOS F	LOS F	Out of Service	
High (6ft)	Max Depth of Water less than 3 ft	LOS A	LOS C	LOS D	LOS F	LOS F	Out of Service	
	Max Depth of Water more than 3 ft	LOS B	LOS C	LOS E	LOS F	LOS F	Out of Service	

The following **Table 2** presents the number of trails affected under three distinct coastal flow scenarios. These trails are categorized by the county, enabling local governments and infrastructure management agencies to effectively plan resiliency strategies and allocate appropriate budgets. The data indicates that Sussex County contains a greater number of vulnerable facilities compared to the other two counties, highlighting the need for prioritized attention in that region.

Table 2. Number of affected trails by coastal flow in Delaware State [9].

County	Total number of Trails	Number of Affected Facilities under Three Projections		
		Low (2ft)	Medium (4ft)	High (6ft)
New Castle	539	38	49	53
Kent	122	34	38	40
Sussex	248	76	113	128

As previously noted, one of the key objectives of this research is to identify trail segments that will be fully lost under various coastal flow scenarios. The following **Table 3** present trails projected to experience complete submersion. Each entry includes the trail's identification number, name, total length, and the county in which it is located. This information is intended to support resiliency planning and resource prioritization at the local level.

Table 3. Fully impacted trails under low coastal flow projection (2 feet) [9].

Trail ID	Trail Name	Distance of Trail (mile)	County
426	Peterson Refuge Boardwalk	0.312	New Castle
25	Bear Swamp	0.121	Kent
26	Boardwalk	0.219	Kent
78	Boardwalk	0.195	Kent
270	AREC Trail	0.18	Kent
287	St. Jones Reserve	0.171	Kent
288	Unnamed Trail	0.021	Kent
5	Unnamed Trail	0.045	Sussex
84	Natter Park Trail	0.08	Sussex
85	Natter Park Trail	0.08	Sussex
179	Canalfront Park Pathway	0.113	Sussex
717	Mispillion Riverwalk	0.032	Sussex
777	Governors Walk	0.016	Sussex
780	Governors Walk	0.048	Sussex
781	Governors Walk	0.022	Sussex
783	Memorial Park Loop	0.112	Sussex
Total Distance (mile)		1.765	

Tables 1-3 are samples for all relative tables regarding the details of trails impacted by different coastal flow scenarios.

The scope of this research includes trails and bike routes across the state of Delaware. Since the findings of this study are intended to support the efforts of the Delaware Department of Transportation (DelDOT) and other agencies responsible for maintaining and improving these facilities, the results for trails are categorized by county: New Castle, Kent, and Sussex.

The following graphs display the level of service for trails under low (2 feet), medium (4 feet), and high (6 feet) coastal flow scenarios for each county (Figures 1-3).

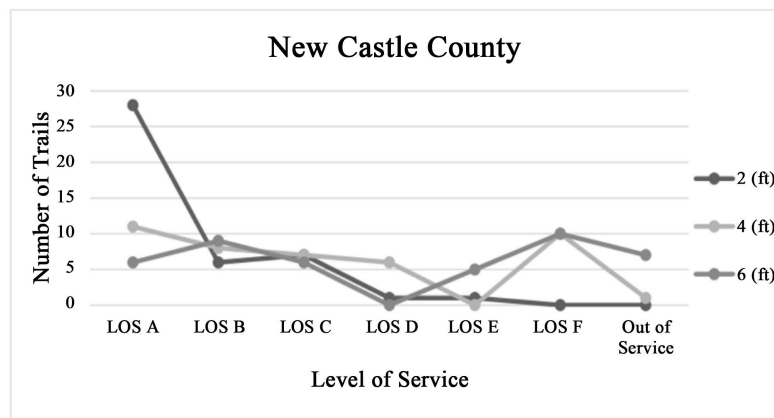


Figure 1. Trail’s level of service under three coastal flow scenarios in New Castle County [9].

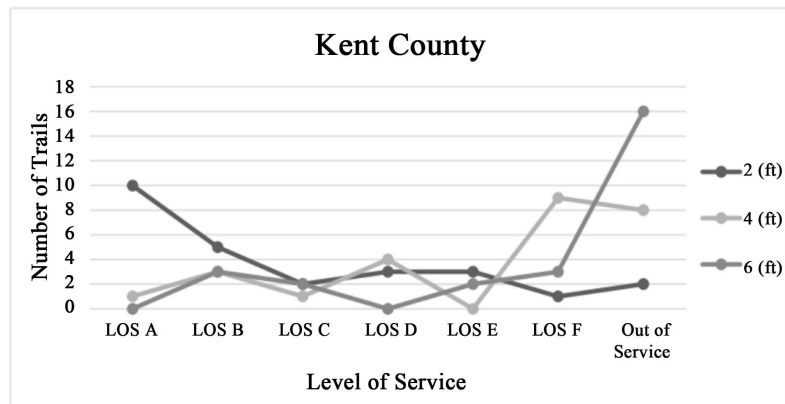


Figure 2. Trail’s level of service under three coastal flow scenarios in Kent County [9].

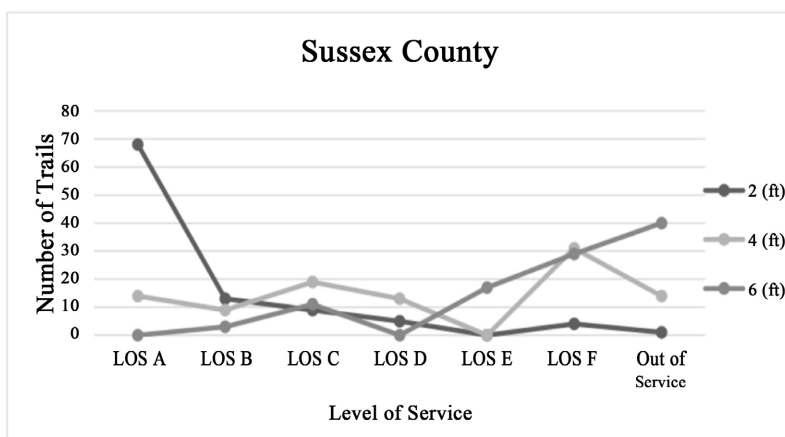


Figure 3. Trail’s level of service under three coastal flow scenarios in Sussex County [9].

The scope of this research includes both trails and bike routes with a primary focus on trails throughout the state of Delaware. Since the findings are intended to inform the Delaware Department of Transportation (DelDOT) and other relevant agencies responsible for the maintenance and improvement of these facilities, the results for bike routes are categorized based on their classification: Connector, Regional, and Statewide. It should be noted that while the same analyses were performed for bike routes, the present manuscript focuses primarily on trail-based results to maintain clarity and scope.

This research focuses on the effects of ecological shifts, particularly coastal flow, on non-motorized transportation facilities across Delaware, including trails and bike routes. Various environmental factors, such as changes in temperature, precipitation, and flooding patterns, can influence travel behavior and infrastructure performance. In this study, the analysis specifically investigates how different levels of projected coastal flow (2 ft, 4 ft, and 6 ft scenarios) may impact active transportation systems.

Geospatial data for trails and bike routes were collected from sources including the Delaware Department of Transportation (DelDOT). Using a digital elevation model (DEM) and coastal flow projections from NOAA, a GIS-based model was

developed to estimate the distance of facilities that may be impacted and the depth of water that may cover them under each scenario.

Findings show that as coastal flow projections increase, more facilities are expected to be affected and service levels decrease accordingly. For example, the number of impacted trails rises by 56.76% from the low to medium scenario and by 78.9% from low to high. Similarly, the total affected distance increases by 60.95% and 90.3%, respectively. While no bike routes are fully impacted under the low scenario, the number of affected routes increases significantly under the higher projections.

County-level analysis reveals that Sussex County, with its extensive shoreline, is more exposed than Kent and New Castle Counties. In Sussex, the number of out-of-service facilities increases by 97.5% when comparing medium and high flow projections. Additionally, connector bike routes show higher exposure and are critical to maintaining the overall network functionality. Investing in adaptive measures for these connectors could enhance the performance and resilience of the entire system.

Finally, coastal flow raises questions of long-term sustainability for urban and regional transportation systems. Active transportation is increasingly promoted as a solution for reducing greenhouse gas emissions, improving public health, and enhancing mobility options. However, if these systems are not designed to withstand future ecological pressures, their role in ecological mitigation may be undermined. Ensuring that non-motorized infrastructure remains viable and safe in the face of coastal flow is therefore essential not only for adaptation but also for the success of broader environmental and transportation policy goals. Forward-thinking design, data-driven risk assessment, and cross-agency collaboration will be critical to safeguarding these networks in the decades to come.

3. Temperature

Global temperature patterns have shifted considerably in recent decades, with consistent warming trends documented across nearly every continent. Each of the past several years has ranked among the hottest ever recorded, and five-year outlooks suggest continued deviation from historical norms. These changes are not isolated to remote regions but are now a defining feature of daily life in urban environments, where infrastructure is increasingly strained by prolonged exposure to elevated heat levels. For the transportation sector, these conditions introduce new challenges, especially for facilities that are exposed to the elements, such as sidewalks, trails, and bike paths.

Secondary data on projected seasonal changes in thermal and precipitation patterns under varying ecological scenarios underscores critical considerations for urban transportation planning in Delaware, particularly within underserved neighborhoods and areas with high reliance on active transportation. Elevated temperatures, especially during the summer months (June, July, and August), are expected to intensify stress in urban centers such as Wilmington, disproportion-

ately affecting residents who depend on walking, cycling, and other active modes. According to the U.S. Census Bureau (ACS Report, 2021), approximately 5% of Delaware workers commute via public transportation and are therefore more likely to encounter challenges associated with heightened outdoor exposure. Moreover, the intensification of localized heat retention in urban areas is likely to exacerbate discomfort and safety concerns during peak daytime hours, thereby constraining the practicality of active transportation for target populations.

Surfaces used in active transportation infrastructure are highly sensitive to thermal stress. Asphalt and concrete, which are common materials for bike lanes and pedestrian walkways, can soften, expand, and crack under extreme heat. These forms of deterioration not only shorten the service life of the infrastructure but also create safety hazards for users. In addition, metal components such as signage, railings, and support structures may warp or become unsafe, especially when combined with direct solar exposure and poor ventilation. The cumulative effect of repeated hot days can be more damaging than isolated events, particularly in regions with aging or minimally maintained infrastructure.

User behavior also shifts in response to hotter conditions. People tend to reduce walking and biking activities during the hottest parts of the day and may avoid routes lacking shade or cooling features. This behavioral change can disrupt the intended functionality of active transportation networks, especially where these routes serve as important links to transit hubs, schools, or employment centers. For urban planners and transportation agencies, these changes complicate demand forecasting and service planning, as infrastructure designed to reduce motor vehicle dependency may see lower-than-expected usage during warmer seasons.

Urban heat islands intensify the challenge. In densely built environments with limited vegetation and high concentrations of pavement, surface temperatures can exceed surrounding rural areas by several degrees. Trails and bike paths that traverse these areas often lack tree canopy or cooling infrastructure, making them uncomfortable or even unsafe during hot periods. This not only discourages use but also exacerbates disparities in mobility access for individuals who rely on walking or cycling as a primary mode of transportation.

Design and planning decisions must now account for sustained heat exposure over long operational lifespans. Materials must be selected not just for durability but also for thermal performance. Cooling features such as permeable pavement, reflective surfaces, vegetated buffers, and shaded rest areas are becoming essential components of new infrastructure projects. Some municipalities are also experimenting with cooling stations, water mist systems, and green corridors that double as both mobility routes and heat mitigation zones. Without such adaptations, the functional reliability of active transportation facilities may decline, especially in the mid- to late-century planning horizon.

This section applies spatial analysis techniques to examine how elevated outdoor conditions influence travel behaviors in economically stressed areas. By lev-

eraging geographic data, we can identify and visualize regions where external environmental stressors coincide with socioeconomic challenges. This method enables a focused evaluation of how prolonged periods of high outdoor intensity may affect daily mobility patterns particularly walking, cycling, and other forms of non-motorized transport and micromobility frequently used in these neighborhoods. Such analysis is essential for informing transportation planning efforts that aim to enhance user comfort and system adaptability.

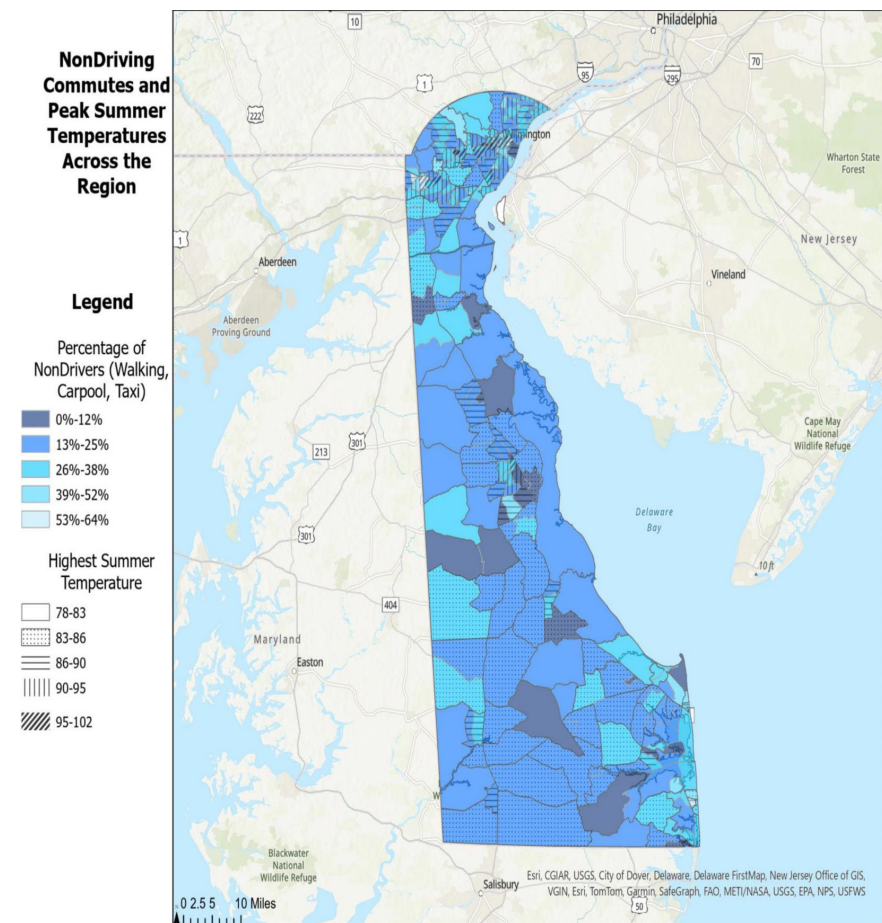


Figure 4. NonDriving commutes and peak summer temperatures across the state.

Figure 4 titled “*Nondriving Commutes and Peak Summer Conditions Across the Region*” presents a detailed view of transportation patterns and their association with peak summer temperature ranges in Delaware, with a focus on populations relying on alternatives to personal vehicles such as walking, carpooling, or taxis. The analysis reveals that in urban centers like Wilmington, a notable proportion of the population (53% - 64%) uses non-driving modes for daily commuting. These same areas also align with higher summer temperature ranges (95 - 102°F), suggesting that individuals traveling without private vehicles may encounter greater exposure to elevated outdoor conditions. This reflects ongoing urban design challenges, as dense city areas with higher rates of non-driving commutes

often have limited green cover and fewer features that help moderate outdoor temperatures (Harlan *et al.*, 2006).

The data presented in the map highlights the value of adaptive design approaches, especially in high-density areas where many residents do not rely on private vehicles. Strategies such as increasing shaded street corridors, enhancing transit infrastructure, and improving pedestrian environments can support more comfortable and accessible travel conditions. These approaches not only encourage the use of sustainable transportation modes but also help manage localized temperature buildup, contributing to improved urban experience and mobility. The observed association between higher outdoor temperature ranges and higher non-driver percentages supports prior findings that enhancements in urban infrastructure can positively influence travel safety and comfort for these populations (Stone *et al.*, 2010). This visualization offers planners and policymakers an important tool for addressing infrastructure effectiveness in future transportation planning.

The connection between long-term temperature trends and sustainable mobility is fundamental. Active transportation remains a cornerstone strategy for reducing emissions, improving air quality, and enhancing public health. However, if pedestrian and cycling infrastructure is not adapted to future climatic conditions, its benefits may be undermined. A resilient transportation system must ensure that active modes remain viable and safe throughout the year, regardless of environmental stressors. This requires integrating ecological-informed engineering standards, proactive maintenance practices, and heat-conscious urban design into transportation planning frameworks at all levels of government.

4. Flooding

Flooding has become one of the most impactful and frequently observed ecological stressors affecting urban environments worldwide. Driven by changes in precipitation intensity, soil saturation levels, drainage limitations, and storm patterns, many cities now face water accumulation events that occur more often and last longer than in previous decades. These events are no longer confined to historically flood-prone regions but are increasingly affecting inland and coastal urban areas alike, disrupting infrastructure systems that were not designed to manage such conditions.

For the transportation sector, flooding presents operational and structural challenges. In particular, non-motorized infrastructure such as pedestrian paths, bike lanes, and recreational trails is highly exposed. These facilities are often located at lower elevations, near natural water features, or alongside roadways with minimal protective drainage. When floodwaters overflow curbs, trail surfaces become submerged, and pooled water may linger for hours or days, especially where stormwater systems are undersized or clogged. In such conditions, not only is access interrupted, but the materials themselves can degrade—pavement can erode, painted surfaces fade, and foundation layers weaken.

Active transportation systems rely on continuity and accessibility. Unlike roadways that may have detour routes or elevated segments, bike and pedestrian paths typically offer limited alternatives once blocked by water. A single impacted segment can break a critical connection between residential areas, transit hubs, and community centers. In many cities, greenways and linear park trails are designed to serve both recreational and commuting purposes; when these are affected by water accumulation, their utility as everyday mobility corridors diminishes significantly. Moreover, prolonged wet conditions discourage public use even after the water recedes due to mud, debris, and safety concerns.

Flood conditions also create long-term damage that is less immediately visible. In areas where infrastructure is repeatedly exposed to water, there is a higher risk of mold, foundation subsidence, and vegetation overgrowth, all of which require ongoing maintenance. Trail surfaces may warp, form potholes, or develop soft spots that become hazardous to cyclists and pedestrians. Without proactive monitoring and repair, the quality and safety of the active transportation network declines, sometimes leading to full closures or costly reconstruction projects.

Designing for these evolving challenges requires a shift in planning strategies. New infrastructure must consider not only flood-resistant materials but also intelligent siting that avoids vulnerable areas where possible. Elevated boardwalks, permeable pavements, and integrated bioswales can help reduce water retention and improve resilience. In some cases, trail corridors are being co-designed as dual-purpose drainage zones or emergency access lanes, capable of serving transportation needs under normal conditions and flood management roles during storm events.

As active transportation and micromobility become more central to sustainable urban mobility, protecting their infrastructure from water-related damage is essential. Cities that prioritize walking and cycling must ensure that networks remain accessible year-round. This means anticipating flood-prone zones during the planning stage, implementing adaptable designs that withstand fluctuating environmental conditions, and allocating funding for rapid response and recovery following heavy rainfall. The resilience of active transportation infrastructure in the face of persistent flooding will play a key role in shaping the reliability and attractiveness of non-motorized mobility in the coming decades.

5. Urbanization

Urbanization continues to shape the structure and function of cities worldwide. As populations concentrate in urban centers, the built environment undergoes rapid transformation, with changes in land use, infrastructure demands, and transportation behavior. This shift is driven by a range of factors including economic opportunity, technological development, and shifting settlement patterns. While urbanization supports growth and connectivity, it also brings about new pressures on infrastructure systems, including those designed for walking, cycling, and other forms of active mobility.

As more land is developed to accommodate housing, commercial activity, and transportation corridors, natural surfaces are often replaced with impervious materials such as asphalt and concrete. This transformation alters local drainage patterns, increases surface runoff during storms, and elevates ambient surface temperatures. These effects are particularly pronounced in areas where urban growth occurs rapidly without adequate infrastructure planning. The outcome is an environment where non-motorized transportation systems—such as bike lanes and pedestrian walkways—are often fragmented, poorly maintained, or exposed to environmental stressors such as flooding and prolonged heat.

Urban expansion often leads to increased traffic congestion, which in turn strengthens the case for investment in active transportation alternatives. However, the design and layout of newly urbanized areas can either support or inhibit these alternatives. Low-density development patterns that separate housing from workplaces and services often discourage walking and cycling due to distance and lack of direct connections. Moreover, wide roadways and car-centered infrastructure present physical and psychological barriers to non-motorized users. Without dedicated space and safety features, walking and biking become less viable, particularly for short- to medium-distance trips within urban zones.

Another critical impact of urbanization is the competition for space. As cities become more densely built, transportation infrastructure must coexist with utilities, green space, parking, and buildings. In this context, allocating space for active modes can be politically and logistically challenging. Yet studies show that compact, walkable urban forms not only reduce traffic but also support local economies and enhance public health. Integrated design that includes wide sidewalks, protected bike lanes, shaded corridors, and secure crossings can greatly enhance the functionality of active transportation in dense settings.

The relationship between urban growth and environmental conditions is also important. As cities develop, changes in land cover and water flow can increase exposure to ecological stressors such as coastal flow and flooding. Infrastructure that is not designed to handle these conditions may experience chronic disruption, particularly in low-lying or poorly drained areas. For active transportation facilities, this may mean frequent closures, damage to surface materials, or long-term usability decline. Proactive designs such as raised paths, permeable surfaces, and integration with green infrastructure can help mitigate these risks and ensure continuity of service.

As one of the earliest settled regions in the United States, Delaware has undergone significant growth, particularly over the past two decades. Satellite imagery analysis shows that urbanization has been a major driver of land cover change across the state. This expansion has contributed to a reduction in ecological services (EPA *et al.*, 2021), correlating with increases in impervious surface coverage, urban hotspots, and a noticeable decline in health of vegetation.

Delaware's urban development has exceeded the threshold of impervious surface (10% - 15%) generally considered sustainable for watershed health (Center for Watershed Protection, 2003). As impervious areas expand, they impact water

systems such as the Delaware River by increasing pollutant levels, elevating flood risk, and contributing to erosion.

Once characterized by dense and healthy vegetation, Delaware now exhibits widespread vegetation loss, especially near the Delaware River and wetland regions. This shift has raised concerns related to air quality and habitat availability for native species. Key drivers of vegetation decline include land-use transformation, erosion, and diminished water quality (Kreeger *et al.*, 2010). Together, these trends reflect the substantial ecological consequences of ongoing urban growth in the region.

Urbanization presents both challenges and opportunities for active transportation. On one hand, it can generate demand for alternatives to private vehicles, reduce travel distances, and make compact, multi-modal transport systems more feasible. On the other, if not managed thoughtfully, it can strain existing infrastructure, limit access to safe routes, and increase exposure to environmental hazards. To ensure that walking and biking remain viable modes of transport in growing cities, urban planners must integrate active mobility into the early stages of land use and transportation design. Doing so will help create urban environments that are more resilient, efficient, and accessible in the face of evolving ecological and social conditions.

6. Technological and Policy Recommendations

The review of existing literature underscores the profound impact of ecological factors on roadway design, revealing the necessity of incorporating strategies in infrastructure planning. Key findings include:

6.1. Coastal Flow

This is a case-specific study, allowing management agencies to reference the results to evaluate the condition of individual non-motorized transportation facilities. Therefore, it is recommended that these findings be used to inform future planning and investment decisions related to trails and bike routes. For instance, if a facility is projected to reach the lowest service level by 2100 under certain coastal flow scenarios, it may not be practical to allocate resources for adaptation. Instead, constructing new, more resilient facilities may be a more effective use of available funds.

In addition, the literature identifies two other environmental stressors that influence transportation systems: flooding associated with intense precipitation, and prolonged periods of elevated temperature. Future studies can extend this research to estimate how these conditions affect non-motorized infrastructure and the travel behavior of pedestrians and cyclists. For flooding, the same spatial analysis method can be applied by replacing the coastal flow model with a GIS-based flood frequency model. To assess the impact of temperature, behavioral data can be collected, for example, through surveys that explore how walking and cycling habits shift in response to higher outdoor temperatures.

6.2. Temperature

Considering these findings, it is important for policymakers and urban planners to support the development of adaptable urban environments that meet the needs of communities facing elevated environmental exposure. One key approach involves enhancing green infrastructure equitably. The addition of parks, green roofs, and street trees can help reduce surface temperatures and provide shared spaces for rest and relief—especially in dense urban areas where access to private outdoor spaces is limited.

Another important strategy is improving public transit systems and pedestrian infrastructure. Expanding and upgrading these services can reduce reliance on personal vehicles, contributing to improved air quality and more balanced surface conditions. At the same time, investments in walkable urban designs such as shaded sidewalks and safer crossings can help make non-driving commutes more comfortable and accessible.

Localized cooling solutions can also be effective. Establishing cooling stations or water features in strategic, publicly accessible locations can provide relief during warmer periods, particularly for individuals who do not have access to indoor cooling or personal vehicles.

Finally, updating building and zoning regulations plays a crucial role. Construction codes can promote the use of reflective materials, adequate insulation, and proper ventilation, all of which contribute to maintaining indoor comfort without heavy reliance on mechanical cooling. Land-use planning should also encourage mixed-use development to reduce travel distances and limit unnecessary exposure to outdoor conditions.

By adopting these strategies, cities can not only improve current living conditions but also enhance their capacity to adapt to future environmental challenges. These efforts contribute to more inclusive and livable communities, ensuring that all residents, regardless of background or mobility, benefit from infrastructure planning.

6.3. Flooding

Flooding, particularly during periods of intense precipitation, poses a growing challenge for the functionality and safety of active transportation and micromobility infrastructure. Low-lying trails, bike routes, and pedestrian corridors are often among the first to experience service interruptions when drainage systems are overwhelmed. To reduce disruption and maintain accessibility, it is essential to integrate stormwater-resilient design into all future non-motorized transportation projects. This includes raised pathways, permeable pavements, and improved grading to divert water away from critical corridors.

Local and state transportation agencies should prioritize the development and maintenance of drainage infrastructure that supports active mobility networks. Integrating bioswales, retention basins, and subsurface drainage into trail and sidewalk design can significantly reduce pooling and washout risks. Additionally,

retrofitting existing facilities in flood-prone areas with such features can extend their operational lifespan and ensure continued access during moderate rainfall events.

Data-driven planning is essential for effective mitigation. Agencies should incorporate flood-frequency mapping and real-time precipitation models into their infrastructure planning workflows. By identifying historically impacted corridors and overlaying floodplain data with trail and bike route inventories, planners can better assess risk and prioritize adaptive upgrades. This approach will also support more efficient emergency response strategies when access routes are temporarily obstructed.

Public communication tools such as signage, mobile alerts, and interactive maps should be developed to inform users of temporary closures or high-water areas. Equipping residents and commuters with timely updates can prevent accidents and encourage safe route planning. These strategies, combined with investment in flood-aware design, will ensure that active transportation remains a reliable and appealing option even during adverse weather conditions.

Finally, coordination between transportation, public works, and environmental agencies is critical to successful implementation. By aligning goals, pooling resources, and sharing data, municipalities can create integrated networks that are not only safe and connected but also capable of withstanding increasingly frequent precipitation-related events.

6.4. Urbanization

Urban growth continues to reshape land use, mobility patterns, and transportation infrastructure. As development intensifies, active transportation and micro-mobility facilities often face pressure from limited space, increased vehicular traffic, and changes in surface conditions. To maintain equitable access and promote non-driving travel, planners must embed walking and cycling infrastructure into all stages of urban development and redevelopment processes.

One key strategy is implementing complete streets policies that require new developments to accommodate all users, including pedestrians, cyclists, and users of micromobility devices. This ensures that sidewalks, crosswalks, bike lanes, and shared-use paths are not considered secondary features but essential components of urban fabric. Encouraging mixed-use development near active transportation corridors also reduces the need for long-distance travel and supports more compact, walkable communities.

Urban green infrastructure should be expanded alongside transportation investments to reduce surface temperature buildup and improve the comfort of outdoor travel. Linear parks, shaded corridors, and tree-lined streets not only improve aesthetic value but also encourage greater use of active travel modes. These features are especially valuable in areas with high-density development where natural spaces are limited.

Preserving and enhancing connectivity is another critical priority. As urbani-

zation intensifies, previously continuous trail networks or bike paths may become fragmented due to new construction or road widening. Agencies should work proactively to maintain connected non-motorized routes through protected bike lanes, pedestrian bridges, and dedicated mid-block crossings. Without continuity, the functionality of these networks diminishes and their usage declines.

Finally, long-term urban planning should integrate geospatial analysis to monitor how land use changes interact with transportation infrastructure. By assessing how trends in impervious surface expansion, population density, and development pressure affect active transportation networks, policymakers can make informed decisions about zoning, transportation funding, and infrastructure priorities that support healthier, more accessible, and more resilient cities.

7. Results and Discussion

Active transportation, including walking, bicycling, and micromobility, has emerged as a vital element in modern urban mobility systems. Micromobility refers to compact, lightweight vehicles such as bicycles, e-bikes, and electric scooters that are typically used for short-distance travel. These modes are increasingly recognized for their potential to reduce congestion, improve urban accessibility, and support more adaptable transportation systems. Technological innovations, including GPS integration, mobile platforms, and Mobility-as-a-Service (MaaS), are making these modes more efficient, user-friendly, and accessible. Cities across North America, including Wilmington and Dover in Delaware, are expanding cycling infrastructure and shared mobility networks to meet growing demand.

At the same time, ongoing ecological shifts are influencing transportation planning across multiple dimensions. Changes in coastal flow patterns, temperature trends, flooding, and continued urbanization are placing new demands on infrastructure and mobility systems. In coastal regions such as Delaware, non-motorized facilities are particularly exposed to surface-level environmental changes due to their proximity to water and ground-level placement. Flooding events have become more frequent and intense due to shifting rainfall patterns, placing pressure on drainage systems and often disrupting access to trails, sidewalks, and bike routes. Similarly, long periods of elevated outdoor temperatures can reduce travel comfort, particularly for cyclists and pedestrians, while also affecting infrastructure durability. In parallel, urbanization continues to reshape the built environment. While cities offer efficiency and economic opportunities, rapid growth often leads to infrastructure strain, disconnected networks, and limited space for non-driving modes of transportation.

Despite these challenges, micromobility and active transportation present valuable opportunities to enhance urban resilience. When supported by strategic investment such as shaded walkways, protected bike lanes, improved drainage, and integrated land-use planning, these modes can help cities adapt more effectively to evolving environmental conditions. They also support broader goals related to accessibility, public health, and sustainable development. As Delaware continues

to grow and adapt, leveraging geospatial data, inclusive policies, and user-centered design will be critical in building transportation systems that remain reliable, connected, and responsive to ecological change.

This study outlines a set of targeted recommendations to enhance the resilience and functionality of active transportation and micromobility infrastructure in response to ecological shifts across Delaware. Key strategies are organized around four primary focus areas: coastal flow, elevated temperature, flooding, and urbanization.

In the context of coastal flow, the analysis emphasizes case-specific planning based on service projections. Agencies are encouraged to prioritize investment in facilities with long-term viability and consider redirecting resources away from those projected to reach the lowest performance levels. The same analytical approach may be extended in future research to assess the impacts of other environmental stressors such as flooding and outdoor temperature on pedestrian and cyclist behavior.

To address temperature-related stressors, recommendations focus on improving outdoor comfort and safety through expanded green infrastructure, enhanced pedestrian networks, and localized cooling features. Updates to building and zoning regulations are also advised to promote energy-efficient construction and reduce exposure to high outdoor temperatures, particularly in compact urban areas. Flooding, especially in areas affected by intense precipitation, poses a substantial threat to non-motorized facilities. Mitigation strategies include incorporating stormwater-resilient designs such as raised walkways, permeable surfaces, and improved drainage. Additionally, geospatial data and communication tools should be leveraged to support real-time risk management and ensure continued accessibility during weather-related disruptions.

Regarding urbanization, the report recommends integrating walking and cycling infrastructure into all stages of urban development. This includes adopting complete streets policies, maintaining connectivity of non-motorized routes, and using geospatial tools to monitor land use changes. Green corridors and shaded travel paths are also highlighted as essential for encouraging safe and comfortable travel in increasingly dense environments.

Together, these recommendations offer a practical roadmap for agencies and planners aiming to strengthen infrastructure performance, improve mobility options, and adapt effectively to long-term environmental pressures across Delaware's transportation network.

The ecological stressors examined in this study do not operate independently. Urbanization increases impervious surfaces, which exacerbates flooding severity by limiting natural drainage. These same impervious surfaces also intensify heat retention, amplifying temperature-related discomfort for pedestrians and cyclists. In coastal areas, urban expansion often pushes infrastructure closer to vulnerable shorelines, increasing exposure to coastal flow hazards. The interaction among these stressors creates compound risks that disproportionately affect active trans-

portation users, underscoring the importance of integrated resilience planning.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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