RESEARCH & DEVELOPMENT

Impacts of CAV-ready infrastructure on vulnerable road users: Guidance for North Carolina's local and state transportation agencies

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16. Abstract

Connected and automated vehicles (CAVs) are of interest to transportation professionals as well as to the general public, given the potential they offer to decrease the incidence and impacts of crashes, to increase traffic efficiency, and to deliver new modes and models for mobility. At the same time, CAVs raise concerns about how they may impact pedestrians, cyclists, and other people in the roadway environment. In the absence of empirical findings on how these modes interact, governments—from local to state and regional—would benefit from guidance to help them prepare for CAVs in the travel landscape while also protecting safety and mobility of all modes.

This project identified CAV-readiness strategies already in place or being considered in 15 U.S. cities in 12 states and interviewed three dozen transportation professionals from those locations, then applied select strategies to intersection design in several North Carolina cities and empirically tested how they may impact perceived safety and accessibility of pedestrians. This project used a mixed-methods design to identify, catalog, visualize, and evaluate strategies to accommodate CAVs at intersections—where interaction among modes is most intense, and developed a hybrid intercept/online survey design to understand how pedestrians experience the infrastructure and surrounding built environment.

This project generated 1) analysis of cities and states leading the way on preparing for CAVs to arrive on city streets in the coming decades, and the strategies they have adopted or are considering; 2) a replicable method for visualizing intersections in order to test various physical design options, supported by a replication reference guide; and 3) a demonstration of surveying non-motorized travelers about the perceived quality and safety of intersections—both existing and redesigned. Key recommendations include facilitating CAV-readiness discussions among diverse stakeholders, designing intersections to serve CAVs but prioritize pedestrian safety and comfort, developing methods to understand impacts on non-vehicular travelers, and supporting research on post-pandemic public engagement.

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Executive Summary

Connected and automated vehicles (CAVs) are poised to fundamentally transform transportation systems and mobility. While CAVs offer potential safety, efficiency, congestion reduction, and expanded mobility benefits, uncertainties remain regarding if, how quickly, and under what conditions these benefits will be achieved. Of particular concern is the impact of CAVs on pedestrians, bicyclists, and other vulnerable road users. As CAV penetration increases, transportation agencies must proactively adapt infrastructure and policies to capitalize on CAV capabilities while protecting and prioritizing non-vehicular travel.

This multifaceted research project reviewed literature, interviewed experts in innovator cities, developed intersection redesigns, and conducted pedestrian surveys to identify emerging municipal strategies for CAV readiness and propose intersection designs that integrate CAVs while maintaining pedestrian and bicyclist safety and mobility.

The literature review revealed debate over projected CAV adoption rates but agreement that CAVs will necessitate changes to infrastructure, laws, and transportation planning. However, clear guidance is lacking on the safe, equitable integration of CAVs with walking, bicycling, and public transit. Interviews with 36 transportation professionals in 15 cities actively pursuing CAV testing and deployment showed they anticipate transformative CAV impacts but lack defined strategies for transitioning to CAV-adapted systems while protecting pedestrian and bicyclist mobility and safety. Most noted CAVs' need for predictability in the roadway environment and discussed modifying infrastructure like lane markings, signs, and signals to better support CAV capabilities. Many also expressed concerns about proposals to restrict pedestrian movements in ways that subordinate convenience and safety of people outside vehicles to smooth CAV circulation. Overall, interviews revealed strong interest in the potential benefits of CAVs but uncertainty regarding effective planning for safe, equitable multimodal system integration.

In response to this knowledge gap, the project team proposed adapting intersections for CAVs using established "protected intersection" principles. This involved: ensuring safety via physical separation from vehicles and speed reduction; maximizing accessibility through intuitive routing and signage; improving comfort with lighting and amenities; retaining necessary space for vehicle queuing and freight access; and accommodating public transit. The principles were applied to develop conceptual redesigns of 5 diverse intersections in small, medium, and large cities across North Carolina. The adapted intersections were rendered in 3D using SketchUp to allow visualization of potential impacts on all travelers.

Pedestrian surveys were conducted to evaluate perceptions of the adapted designs but garnered very few responses, revealing shortcomings of traditional in-person intercept survey methods in a post-pandemic world. Difficulties contacting and recruiting survey participants in the field highlight the critical need for innovative public involvement techniques that seamlessly combine digital technology with inclusive in-person engagement.

Key recommendations relevant to state DOTs include: facilitating broad discussion of CAV deployment risks, benefits, and planning among diverse transportation stakeholders; proactively designing CAV-ready intersections and road segments to inherently prioritize pedestrian and bicyclist safety and convenience over vehicle throughput; developing and pilot testing new methods to meaningfully understand localized impacts of CAV-adapted infrastructure on non-

vehicular travelers; and supporting continued research on post-pandemic transportation public involvement.

In conclusion, this exploratory multi-method project revealed substantial interest among transportation professionals in guidance for safely and equitably integrating CAVs and non-motorized modes into multimodal systems. While the proposed application of protected intersection principles represents one potential approach, continued research and knowledge development is critical as CAV adoption increases. State DOTs must take a leadership role in ensuring infrastructure and policies enhance mobility options and safety for travelers of all modes. Adapting intersections to serve CAVs while protecting vulnerable road users can be an early step, but fully realizing the potential benefits of CAVs requires commitment to safety, equity, and community engagement. This project produced several actionable resources to aid state DOTs in evidence-based CAV readiness, but urgent work remains to prepare transportation systems for an uncertain CAV future that promotes the public good.

Introduction and Background

Connected and automated vehicles (CAVs) are of interest to transportation professionals as well as to the general public, given the potential they offer to decrease the incidence and severity of crashes, to increase traffic efficiency, and to deliver new modes for mobility. At the same time, CAVs raise concerns about how they may impact pedestrians, cyclists, and other people in the roadway environment who already are threatened under present conditions, and who could be further harmed by CAVs and the infrastructure adapted to support them. As part of the array of new mobility modes and transportation technologies (e.g., automated vehicles, scooters, ride-hailing, and more) expected to become increasingly common on roads and streets in the coming decades, CAVs raise both expectations and uncertainty about the future of travel and about the engineering, systems and operations, and governance that they will require. In the absence of empirical findings on how these modes interact, governments—from local to state and regional—would benefit from guidance to help them prepare for CAVs in the travel landscape while also protecting safety and mobility of all modes. While the current unsettled and changing conditions may give rise to stop-gap and temporary measures, a systematic exploration of policies, programs, and infrastructure for CAVs would inform an evidence-based approach to CAV-readiness that addresses safety and mobility for people outside of vehicles. Useful resources would include a review of CAV-relevant infrastructure and policy in cities and states that are innovating in this realm, a demonstrated technique to visually represent infrastructure adapted for CAVs, and a survey tool to evaluate the pedestrian experience of multi-modal and CAV-ready intersections.

Interest in—and concern over—the anticipated arrival of CAVs in street-level traffic intersects with the mission of the North Carolina Department of Transportation (NCDOT) to provide mobility, access, and safety to the state's residents and visitors, while promoting economies, protecting the environment, and responding to public priorities. With CAVs widely predicted to become much more common on public roadways in the near future, and with continued evolution of CAV technology and claims about safe operation across various environments, uncertainty and skepticism persist, leaving policymakers and planners to prepare for a CAV future with scant empirical evidence or tested tools or policies. Recognizing the potential for dramatic gains in safety and mobility, NCDOT has a generally favorable, if cautious, stance toward CAVs. Given its role in building and operating roads, registering vehicles and licensing drivers, and establishing and enforcing laws and regulations, NCDOT will necessarily be deeply involved in any transition to a CAV-adapted transportation landscape.

Any CAV transition will require more than just the technology to automate and connect vehicles—with each other and the environment. Critical components of CAV environments include institutional and legal support, stable funding, expertise in designing and managing CAVs, and communication among agencies and with travelers. North Carolina is among those states that already have established some level of institutional and legal framing, stable and reliable funding, practices relating to engineering and road management, and relationships with the private sector. As cities and states consider how to adapt infrastructure and policy to accommodate CAVs, some experts have raised the alarm that streets and intersections may become hostile to pedestrians, bicyclists, and other non-CAV travelers. Notwithstanding rosy predictions of smooth CAV operation across a range of future environments, technology currently deployed in vehicles and infrastructure falls short of the goal of safe interaction of

CAVs with people when they are not in vehicles. While transportation professionals at various levels confront the need for policies and infrastructure that rise to the demands of the time, evidence-based guidance on CAV impacts and infrastructure needs is scant.

Purpose and Scope

This project was designed to provide timely and accessible resources that support local and state transportation professionals in North Carolina in preparing for CAVs while protecting safety and mobility of travelers of all modes (Figure 1). That involved first identifying, cataloging, and evaluating CAV-readiness strategies employed in a sample of CAV innovator cities, and interviewing transportation professionals in these cities to extract key themes and lessons. A second component of this project involved exploring how to design intersections to effectively accommodate CAVs while preventing these sites from becoming hostile to pedestrians, cyclists, and other non-CAV travelers. Urban intersections are a useful focus, because they are where multiple modes interact with particular intensity and complexity, and because they are likely to be managed by municipal-level professionals with deep familiarity with local conditions and needs. Finally, the project developed and deployed a tool to survey pedestrians crossing intersections, to evaluate their perceived safety and comfort in both the existing intersection and a visualization of the same intersection adapted for CAVs and other modes.

The resulting analysis of CAV-innovator cities, demonstrations of intersection visualization and pedestrian intercept surveys, and reference guide provide a collection of resources that may be used by transportation professionals as well as the general public interested in design and deployment of safety measures for complex multimodal infrastructure.

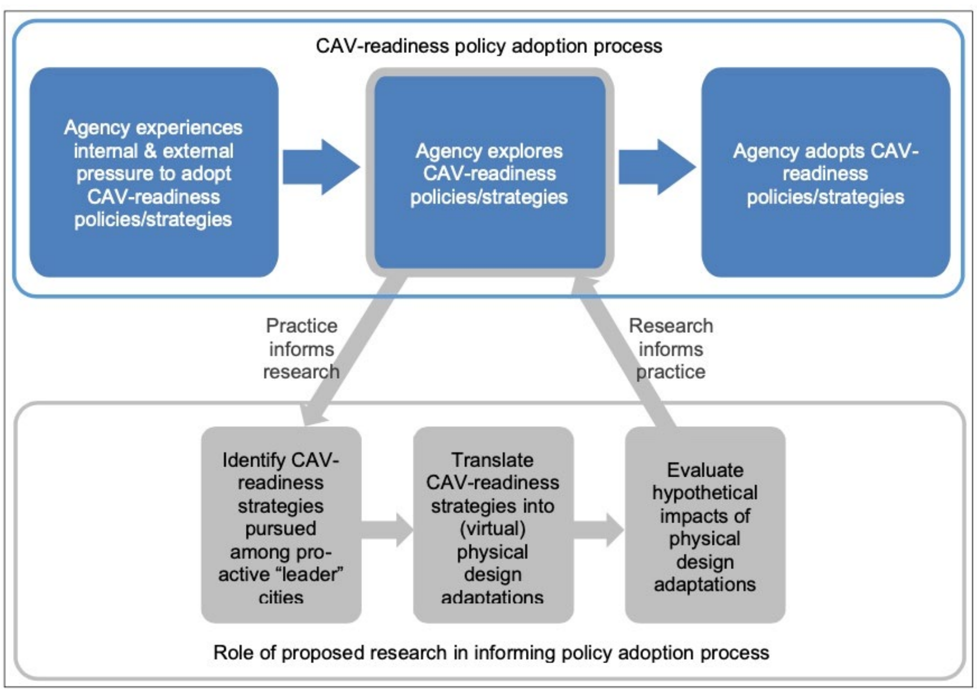

Figure 1. Conceptual framework for project process and outcomes to inform CAV-readiness

Research Approach

This mixed-method project involved several phases to develop resources for transportation professionals seeking to understand and prepare for CAVs in mixed traffic (motorized and non-motorized), with a particular focus on intersections, where modes interact with the most intensity and complexity. Phases include:

- Identify and describe—conduct thematic analysis of documents and interviews with experts to generate a set of common CAV-readiness strategies and lessons,
- Visualize—translate identified strategies into renderings of existing intersections and hypothetical designs of future CAV-adapted intersections that minimize adverse safety and accessibility impacts on other roadway users,
- Evaluate—analyze empirical data on pedestrians' perceived safety at existing and hypothetical future CAV-ready intersections, and
- Recommend—report on demonstrations and best practices for adapting infrastructure for CAV-readiness and for surveying and communicating with the traveling public.

Following this introductory discussion of purpose, scope, background and general approach used in the project, this report summarizes the literature on the state of knowledge and debate relating to CAVs and their likely impacts, municipal and state innovation in this domain, emerging discussions about engineering and design to accommodate CAVs, and best methods for visualizing intersections – for both current conditions and hypothetical future designs (Figure 2), and for surveying travelers about perceived safety and comfort in the built environment. Following the literature are sections devoted to objectives, methods and data, findings and analysis, discussion, and conclusions, as well as technology transfer and workforce development. Literature cited and appendices complete the report.

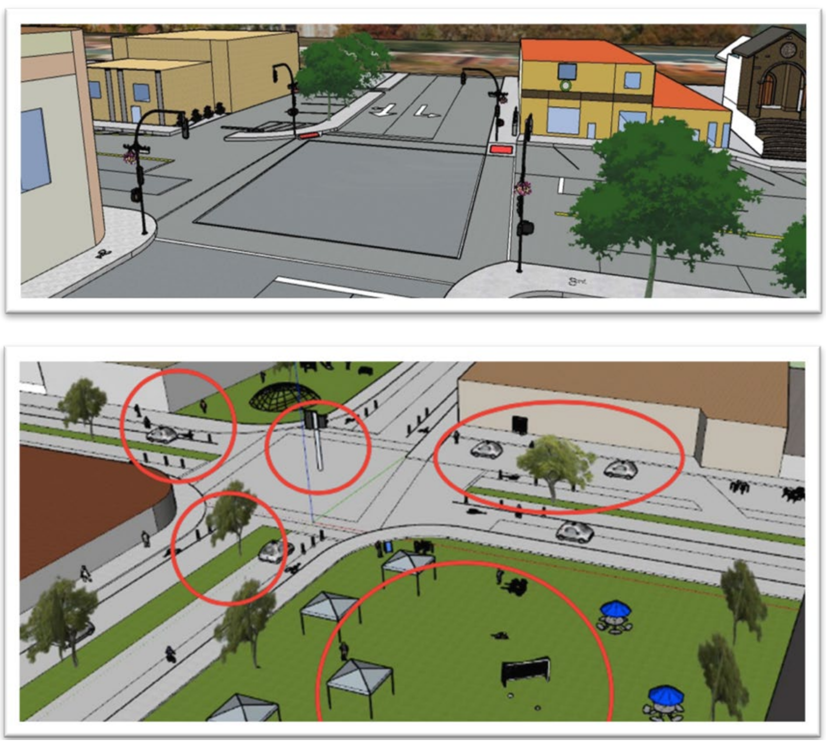

Figure 2. Renderings of W. King & Water Streets in Boone, current condition (upper) and hypothetical future (lower)

Literature Review

As the age of 'autonomous urbanism' approaches, it is becoming increasingly apparent that our transportation systems—policies, norms, land use patterns, and physical infrastructure—will need to evolve in order to both accommodate and capitalize on connected and automated vehicles. Massive uncertainty remains, however, about how CAVs will interact with and shape the transportation system, including how we design and use physical components (roadways, intersections, and conflict points), and how safety and mobility of non-CAV motorists and other travelers will fare in CAV environments. This research seeks to understand and eventually inform municipal CAV-readiness strategies using physical design and policies regulating the use of urban transportation infrastructure. Intersections are ideal targets for early-stage CAV readiness interventions, both because they are where CAVs, non-CAV vehicles, and other road users will interact with intensity and complexity, and because they offer enormous potential for congestion reduction through rationalized access and use of the infrastructure.

Theoretical framework

Despite manufacturer claims that CAVs ultimately will be able to maintain optimal performance regardless of infrastructure quality or design, safety shortcomings in current technology—particularly with respect to how CAVs interact with humans—suggest that pressure will build for municipal transportation departments to implement stopgap or permanent infrastructure interventions in order to ensure the safety of all road users. Furthermore, many of the potential performance gains associated with CAVs will require specialized infrastructure, along with complementary policies governing access to and use of that infrastructure. Cities may also seek to capitalize on the opportunities presented by a fully automated, shared-mobility system to reallocate road space to other land uses and create more efficient, compact, and walkable development. Finally, many cities—from booming high-tech cities in the south (e.g., Austin, TX) to legacy cities and small towns of the northeast and Midwest (e.g., Boston, MA and Saginaw, MI)— have initiatives in place to attract investment by CAV manufacturers looking for new locations to pilot various CAV technologies. Accordingly, many transportation agencies are working on CAV-readiness initiatives that will help them cope with years or decades of mixed CAV, manually driven, mass transit, and non-car traffic, with implications for infrastructure design and use.

While the technology used to identify and avoid colliding with pedestrians and other people in the roadway environment is improving, CAVs have yet to demonstrate the ability to consistently save lives. A well-publicized 2017 pedestrian fatality involving an Uber CAV led many experts, observers, and agencies to call for transportation systems and infrastructure to be transformed now, capitalizing on the potential performance gains and efficiencies of CAVs to ensure a safe, equitable, livable mobility future for all. The alternative is to play policy and technology catch-up in a dangerous and uncertain environment.

However, given the pace of technological innovation in CAV manufacturing, coupled with lack of clear communication channels between industry and the public sector regarding the safety and operational performance of current CAV technology, there is little concrete guidance and few established best practices to which city leaders can turn to guide their CAV-readiness efforts.

Prior research suggests that when practice must evolve in the absence of established models to guide that evolution, cities will respond in a variety of ways. A handful will take the lead, experimenting with creative, context-sensitive solutions that may be informed by outside sources but ultimately spring from internal innovation. Others will wait, either for top-down instruction or until they identify a peer 'leader' city to follow. The push for CAV readiness may follow a similar pattern, wherein innovator-cities experiment with a diverse array of context-sensitive strategies and change driven internally (by city leaders, elected officials, and staff), while 'follower' cities wait for public pressure and external guidance. Anecdotal evidence supports this: An on-going collaboration between Bloomberg Philanthropies and the Aspen Institute maintains a list of over 100 cities worldwide that are already openly working on CAV-readiness strategies, both with and without input from industry; nearly all of them appear to be charting their own responses to CAVs, and accumulating useful knowledge and experiences with a range of CAV- relevant technology, programs, and policy. There is a critical need for external, evidence-based guidance to which these cities may turn as they develop and implement their own CAV readiness strategies.

This literature review covers several areas:

- Projections and speculations regarding the rate of uptake of CAVs,
- Potential implications of an increasingly CAV-dominant vehicle fleet for the safety, convenience, and accessibility of people when they are walking, cycling, or otherwise present in the roadway environment,
- The role of local and state governments in understanding and adapting to the evolving operational needs of CAVs,
- Best practices for accommodating and protecting non-vehicular road users in a CAV-future, and
- Strategies for engaging with the public to understand and communicate potential impacts of CAV-adapted intersection designs on non-vehicular road users.

CAVs on the Horizon

The timing and extent of CAV penetration onto U.S. roads remain uncertain and contentious, against a mixed backdrop of promising advances and repeated setbacks. Potential benefits include not only sharply reduced crashes (and attendant fatalities, injuries, and property damage), but also space efficiency (requiring less road capacity), energy efficiency (predicated on the assumption of electric vehicle technology), lower parking demand and increased mobility—all vigorously contested in professional debates. Early excitement about rapid and smooth mixing of CAVs on our streets has met with widespread awareness that the technologies—as sophisticated and impressive as they are—do not assure harmonious and efficient interaction of CAVs with other road users or adequately protect the safety of non-motorized travelers. Transportation professionals may lack confidence about the CAV transition and the resources needed, while non-motorized travelers may worry that their already tenuous access to mobility on public roads will further erode, compromising their safety and comfort.

All this highlights the need to debate the intricacies of a CAV transition now, rather than leaving local and state agencies to play policy and technology catch-up in an uncertain and changing environment. Transportation planners and state and local officials would benefit from resources relating to technology, design, and policy at the seam of CAV preparation and protection for all people in the roadway environment.

CAV Adoption

Adoption and diffusion of innovation has been studied for decades across sectors and disciplines (Rogers, 2010). Hardman et al. (2019) liken AV early adopters to those in other arenas of technology, with 'pioneers' adopting early, 'laggards' at the tail end, and others covering the territory between. The economic literature on diffusion of technology, applied to AV adoption, suggests that people make decisions based on personal interests even in the presence of technology and knowledge changes in the marketplace (Kaplan et al., 2019). As the cost to own AVs declines and options grow, the pattern seen in other technologies is likely to be replicated with AVs—rising VMT, vehicle ownership, and possibly emissions, along with other new and complementary innovations. The mechanism for adoption by consumers is likely to be complex, sensitive to individual traits as well as government functions. Social networks and information sharing among peers may be important in CAV adoption (Talebian & Mishra, 2018). Some innovations in the transportation sector (such as car-sharing) may be dampened by the variety and number of actors involved, and the difficulty in overcoming the inertia of established practices, for which the tools of governance are not well-suited (Akyelken et al., 2018).

Political science provides some framing for understanding how transportation innovation and relevant policy may be taken up by early-adopting cities, and the conditions that promote policy learning and willingness to adopt innovations, such as strong networks, lessons from multiple sites, and financial and institutional support (Marsden et al., 2010). Docherty et al. (2018) note the need for careful shepherding of change, including technological innovation with the power to revolutionize mobility for individuals and society, while retaining public value as a key goal in managing both benefits and negative externalities that flow from the transition. Careful negotiation of a transition is critical as technological change outpaces the capacity of governance and social systems to absorb it: "A failure to address both the short and longer-term governance issues risks locking the mobility system into transition paths which exacerbate rather than ameliorate the wider social and environmental problems that have challenged planners throughout the transition." Bosch et al. (2018) advise policymakers to exercise caution in making technology-dependent promises, and to promote AV-relevant policies that tie into or complement existing systems.

Bajpai (2016) notes the approaching convergence of innovations in vehicles—automated, low-carbon, and accessible, with potential positive externalities in safety, fuel efficiency and emissions reduction, and mobility for underserved populations (e.g., young, old, and people with disabilities), although the potential for congestion relief from still-rare technology is difficult to assess until there is more time to observe and measure impacts and risks. As AVs increasingly use our roads, and the legal, social, and transport questions they raise are discussed and resolved, cities may be transformed (Duarte & Ratti, 2018). Vehicles may look different, congestion may decrease—or increase, and allocation of road right-of-way and adjacent land uses may change, with near- and long-term shifts in travel behavior, residential location, and more. There is general acceptance that AVs have the potential to disrupt our transportation systems, although without any consensus on the time horizons for dominance by fully automated vehicles. Also still contested is whether that disruption will be negative, positive, or—most likely—a mix. While recognizing potential benefits of safety, reduced travel times and congestion, increased fuel efficiency, and lower parking demand and costs, Fagnant & Kockelman (2015) also note that costs for implementation are daunting, and standards for licensing and testing vary across states, with other unanswered questions relating to liability, security, and privacy, and uncertainty about reconciling new technology and operations with existing systems.

Potential implications of CAVs for pedestrians, cyclists, and other non-vehicular road users

In theory, CAVs have the potential to improve safety for pedestrians, cyclists, and other non-vehicular road users by reducing the impacts and likelihood of errors that lead to crashes. However, this potential relies on *ceteris paribus* assumptions of human behavior, as well as physical and operational characteristics of transportation infrastructure and the policies that govern its use. A growing number of studies have challenged these assumptions.

For example, in a study using virtual reality, Kalatian & Farooq (2021) found that pedestrian wait times at unsignalized crosswalks increase in the presence of CAVs. The study also found that built environment factors, such as road width, influenced pedestrian wait times, with pedestrians waiting longer to start crossing when roads were wider and lacked medians. Longer waits for safe gaps may lead some users to make riskier decisions, including darting out into traffic and counting on the CAV to take appropriate evasive action (e.g., Anderson et al., 2016; Millard-Ball, 2018).

Infrastructure itself is likely to change, even absent deliberate policy. Shaheen et al. (2022) point to the rapid shift toward tactical urbanism during the COVID19 pandemic. Across the country, residential streets converted to shared spaces, and downtown roads saw curb lanes converted to parklets and retail spaces. This was typically achieved through the use of traffic cones, jersey barriers, signs, barrels—whatever equipment local agencies had on hand. Such changes are likely to present operational challenges for CAVs, compelling transportation agencies to invest in standardized "tactical urbanism" equipment for curb space allocations in advance of future disruptions and pre-emptively convert residential streets to pedestrian-priority spaces as a general practice.

Then there is the question of whether CAVs will lead to more or fewer vehicle miles traveled on public roadways, and concomitantly more or less demand for safe, convenient, affordable alternatives (i.e., transit, walking, cycling, micromobility) and more or less demand for location-efficient land (Litman, 2014; A. Shaheen & Cohen, 2018; Soteropoulos et al., 2019).

Given the growing concerns over intersecting and existential threats—climate change, natural resource exploitation, social isolation, and habitat loss to name a few—exacerbated by overreliance on automobile-based transportation, there is broad public support for policies that rebalance road design to prioritize safety and convenience for people walking, riding bicycles, and using public transportation (Botello et al., 2019).

Two of the most vexing challenges that threaten the potential performance of CAVs—the unpredictable behavior of people in the roadway environment and the degraded quality of physical roadway infrastructure—also represent an opportunity. The potential spatial efficiency gains of a CAV-dominant vehicle fleet are well documented (e.g., Riggs et al., 2020). As more conventional cars are replaced by level 4 and 5 CAVs, effective highway capacity will increase, allowing DOTs to shift funding away from roadway expansions toward safe, dedicated multimodal infrastructure. In many situations—particularly in urban settings—this multimodal infrastructure will be able to fit within existing roadway footprints, taking advantage of CAVs' ability to operate efficiently in less space (fewer, narrower lanes) than human-driven cars (California Multi-Agency Workgroup For Healthy and Sustainable Communities, 2018).

Measures that may reduce unpredictability of problematic pedestrian behaviors include investing in more pedestrian- and bicycle-friendly roadway and intersection designs, such as refuge islands, shorter crossing distances, protected bikeways, dedicated signals, shorter wait times, and more user-friendly routes (e.g., Kalatian & Farooq, 2021). Such protected infrastructure is increasingly urgent in light of challenges CAVs are known to face in detecting, identifying, and predicting behaviors of pedestrians and bicyclists (Automated Vehicle Safety Consortium, 2022). Moving toward more pedestrian-friendly roadway designs, with protected medians and narrow travel lanes that shorten crossing distances, may avert these behaviors (Kalatian & Farooq, 2021). Local officials recognize the coming changes, even if the course of action is not always immediately clear. This research explores how some are contemplating upgrading infrastructure to prepare for CAVs, and whether and how to accommodate pedestrians and bicyclists in those upgrades.

CAV readiness: The role of local government in understanding and adapting to CAVs

CAVs and Multimodal Transportation Planning

Multimodal transportation planning considers the needs of not only motorized road users, but also non-motorized travelers (NMT). In a transportation landscape already fraught with danger, inconvenience, and invisibility for people outside of vehicles, CAV-adapted infrastructure and policies offer both new dangers and complications, and possible relief, through reallocated rights of way and compact walkable environments that accommodate all modes (Fayyaz et al., 2022; Lee & Goulias, 2018; Metz, 2018; Schlossberg et al., 2018).

Local governments vary in their capacity to innovate in CAV preparation, with some limited by staffing and resources, community priorities, or special circumstances, while others have the wherewithal to innovate, by initiating pilots, programs or policies that position them to lead the CAV transition and offer a path for other cities to follow as circumstances permit. The documented history of the uptake of innovation (Rogers, 2010; Yuen et al., 2021) suggests that a small group of early adopters (in this case, municipalities and their transportation professionals) may emerge as innovators, taking the lead on developing and testing CAV-readiness strategies, and operating in a setting that allows or promotes experimentation. Such innovators provide a critical pool of experience and new knowledge from which other cities, and society at large, can draw and benefit.

CAVs in the Transportation Planning Landscape

The question of whether AVs will reduce or increase congestion and emissions remains disputed (Metz, 2018; Pakusch et al., 2018; Wadud et al., 2016). Shared AVs could reduce the cost of taxis, but because AVs may 'deadhead' (travel empty), congestion could increase, raising the need for regulation (Metz, 2018). Policymakers will need to be alert and attentive to judge whether AVs will improve or exacerbate congestion, and whether they offer low-cost mobility or impact the number of private cars. Pakusch et al. (2018) likewise raise the uncertainty of whether CAVs will reduce congestion and emissions with smoother traffic flow and fewer vehicles, or whether the comfort and efficiency that CAVs offer may instead increase demand and worsen conditions. Simoni et al. (2019) argue that trips and VMT are likely to rise with widespread use and sharing of AVs, offsetting some of the likely benefits of congestion relief, while Rodier et al. (2020), modeling 100% AV penetration in the San Francisco Bay area, predict rising travel and emissions in the absence of policy interventions. At the same time, demand might be moderated by congestion pricing and road tolls. While CAVs are likely to transform transportation and mobility, with benefits beyond safety and convenience possible, including reduced emissions and greater energy efficiency, such improvement may not automatically generate environmental benefits (Taiebat et al., 2018).

Along with additional capacity and convenience that innovation may usher in, vehicle automation and connection technology also raise the specter of weakening traditional public transportation, although Buehler (2018) asserts that mode likely will remain relevant because of the space efficiency it offers, particularly at peak hours in urban areas. The mandate for transit to serve the underserved likely will hold—and could benefit from emerging CAV technology, if carefully integrated and coordinated across mobility models. While transit may benefit from first-mile/last-mile gap-filling by AVs, private sector interests could shift ridership and weaken the public mandate for transit (Alessandrini et al., 2015; Currie, 2018; Pakusch et al., 2018).

As AV technology rapidly evolves, some states already have legislation on the books to address testing, deployment, and safety (Hubbard, 2018b, 2018a). With expected benefits in safety, capacity, productivity, mobility, and congestion relief, as well as challenges in terms of costs, liability, privacy, security, and lost jobs, legislatures have adopted various strategies to address AVs. Hubbard (2018a) reported 21 states plus the District of Columbia with legislation on the books, and six others with executive orders. Even if federal legislation were to be passed, states will have important responsibilities for licensure, registration, insurance, infrastructure, emergency response, traffic controls and enforcement, and more.

Cervero (2017) argues for a strong and varied mobility marketplace that welcomes innovation and new technologies, to increase options in the traditionally privatized auto transportation landscape in the U.S., and to provide more mobility with less waste. Lewis et al. (2017, p. 3) also comment on legislation, noting how AVs differs from other technology: “With private industry, not government, leading the research and development of the technology, the critical role of policymakers is to continue to foster this innovation while ensuring public safety.” The promises of better transportation from AVs are not tied exclusively to the technology, but rest on changes in the delivery of mobility, such as car-sharing, reduced parking, and filling mobility gaps for specific populations (Alessandrini et al., 2015). Mobility as a service (MaaS) is a concept gaining currency in transportation and mobility planning, with the potential to transform urban mobility (Li & Voege, 2017); MaaS depends on broad dispersion of handheld information technology to let users access regional multimodal mobility services.

Who is (Getting) Ready for Connected and Automated Vehicles?

The benefits CAVs offer in mobility, efficiency, and safety (Crute et al., 2018), while compelling, are not assured, with vigorous debate about the direction (positive or negative) and scale of changes in crashes, VMT, and emissions. Given this uncertainty, pilot programs are useful for testing assumptions, demonstrating technology, and mapping out ways to accommodate CAVs in transportation networks and build acceptance among travelers. Discussion and debate continue relating to technology (connecting vehicles and the environment), ownership and shared mobility (e.g., ride-hailing, shared ownership, mobility as a service), parking and curb regimes, and more. For each of the potential benefits, there are counter-arguments, including concerns about how CAVs will interact with non-motorized travelers and vulnerable road users, and the volume of data needed to support Level 5 (fully automated) vehicles. Of particular interest are intersections, where travelers of all modes meet and negotiate passage most intensely. There is little standardized guidance available for local governments to accommodate CAVs in street networks that include pedestrians, bicyclists, and other non-vehicular road users.

The accumulated literature on CAVs has focused heavily on their intense engineering and data needs, as well as on the compelling but still unproven gains in safety, energy efficiency, congestion reduction, and increased mobility. Less attention has been devoted to how CAVs may impact non-motorized travel and their modes shares, or to possible downstream effects such as land use, road space allocation, and travel behavior—in and out of vehicles. Given the still-maturing technology and limited penetration of CAVs in the road network, it is not surprising that much of the discussion has been speculative. Even so, some local governments and state agencies have embarked on testing and demonstrating CAVs and associated technologies—providing data for this study into the conditions that motivate these innovator cities and the insights and expertise they are able to offer.

Protecting non-vehicular road users in a CAV-future

The MUTCD calls for full separation of CAVs from non-car modes, with pedestrians, cyclists, and users of micromobility devices having dedicated spaces to reduce the likelihood of conflict, including ‘gaming the system,’ between CAVs and other road users. Ensuring this separation and preventing ‘gaming’ will not come about through enforcement (either of separation between modes within roadways or of access to roadways), but through provision of facilities that appeal to the specific needs of pedestrians, cyclists, and other people not traveling in a car.

Protected intersections have gained popularity in the US as a means to improve both safety and compliance for pedestrians and bicyclists by giving users a clearly defined, dedicated path through the intersection (Semler & Sanders, 2020). Protected facilities typically involve setting bicyclists and pedestrians back from the curb on the approach and departure from an intersection, using bulb-outs and corner islands to provide protected areas for pedestrians and cyclists to wait for traffic signals, and orienting crossings at 90 degree angles to motor vehicle traffic and curbs in order to minimize crossing distances and improve visibility. Crossings, which are often raised to curb height to further improve visibility, tend to be set back from the intersection so that there is room for a turning motor vehicle to wait, out of the way of through traffic, for pedestrians and cyclists to clear the crossings. Motor vehicle stop bars are located behind the crossings. The raised crossings and corner islands also function as traffic calming, reducing speeds of vehicles approaching and turning in the intersections (Deliali et al., 2020, 2021; Gilpin et al., 2021). Signals may be timed to give pedestrians and cyclists exclusive phases or leading intervals, depending on mode shares and context (Stanek & Alexander, 2016). Protected intersections have been shown to greatly improve both safety and comfort for pedestrians and cyclists, thereby increasing compliance and predictability—without impeding traffic flow among motorized road users (Lyons et al., 2020; Monsere et al., 2020; Preston & Pulugurtha, 2021).

Elements of protected intersections can work to achieve both the aim of maximizing the potential efficiency of CAVs and providing safe, comfortable infrastructure for pedestrians, cyclists, and other people when they are not in cars.

Safety and comfort for pedestrians and cyclists

Protected intersections improve safety and comfort for pedestrians, bicyclists, and other non-road users by reducing motor vehicle speeds, reducing the number and complexity of intermodal conflicts, and improving predictability and compliance among all road users (Lyons et al., 2020). These factors improve safety by reducing the risk of a collision-prone scenario arising, reducing the likelihood of a collision occurring if a collision-prone scenario does arise, and reducing the severity of a collision if one occurs. The specific design features typically employed to achieve these benefits are described in Table 1.

Table 1. Principles of protected intersections

Design principle	**Objective**	**Safety benefit**		
		Risk	**Likelihood**	**Severity**
90 degree crossings: Tighten turning radii, align intersection legs at right angles, use bulb outs and islands to arrange travelers at 90 degrees to each other at conflict points	Shorten crossing distances	X		
	Improve visibility between modes		X	X
	Reduce vehicle speeds		X	X
Visible, protected waiting areas: Use bulb outs and islands to provide raised protected areas for users to wait for a safe opportunity to cross. These areas can be further protected with bollards or concrete planters. If necessary, mountable curbs can be used to ensure access by emergency or freight vehicles	Reduce exposure to errant motorists while waiting for a crossing signal	X		
	Reduce stress and improves comfort for non-car travelers (thus increasing likelihood of compliance with signals)	X		
	Improve predictability	X	X	
	Improve visibility between modes		X	X
	Shorten crossing distances	X		
Simple maneuvers: Break complex turning movements into simple ones through signal timing, protected islands, and providing space for motor vehicles to safely wait for peds/bikes to clear conflict zones	Reduce cognitive burden for all road users	X	X	
	Improve predictability	X	X	
	Reduce stress and improves accessibility for non-car travelers			
Curb-level crossings: Raise pedestrian and bicycle crossing routes to curb level where possible	Improve visibility between modes		X	X
	Reduce motor vehicle speeds		X	X
	Improves comfort and accessibility for non-car travelers			
Dedicated and automatic countdown signals: Use dedicated, ped/bike specific signals to give non-car travelers exclusive crossing phases or leading intervals and accurate information on wait times. Incorporate them into signal phasing to shorten wait times and eliminate need to press a button	Reduce number of conflicts	X		
	Reduce complexity of conflicts	X	X	
	Improve predictability and compliance	X	X	
	Reduce cognitive burden for all road users	X	X	
	Improve comfort and accessibility for non-car travelers			
	Reduce wait times for non-car travelers	X	X	

However, it is unclear whether protected intersections—which while improving safety often require pedestrians and cyclists to take less direct routes through intersections than they would otherwise take—will be effective with CAVs. Will users eschew the provided separated routes in order to follow more direct paths, knowing that CAVs are programmed to avoid them?

Understanding and communicating impacts

Public surveys about the traveler experience of crossing intersections were part of this project as designed, serving as a first demonstration of creating 3D renderings of intersections as a tool for planning for CAVs, and for effectively engaging the public on current and future travel conditions. This exploratory study generated empirical data from a small sample of travelers reporting on their perception of the comfort and safety of intersections in three North Carolina cities. Of greater likely value than that small dataset, though, is knowledge gained about changing conditions for traditional intercept surveys, barriers encountered in using those established methods for querying the public about their experience moving though the built environment, and insights gained on the need for different survey techniques and technology for the purposes of this inquiry.

Increasingly, we experience the modern world through visual representations, with screens and touch interfaces often leading us through our daily routines—shopping, working, and moving. Transportation is among the most data-intensive sectors, where data-hungry programs manage traffic, inform travelers of routes and schedules, store information, and operate systems and sometimes vehicles. We endeavored in this study to elucidate the human experience of traveling through physical (existing) and visualized (3D) intersections. The visualizations both present current travel conditions and imagine future intersections adapted for CAVs mixed in with conventional motorized vehicles and non-motorized travelers (most commonly, pedestrians and bicycles). For the purposes of this study, we sought to identify a visualization tool that could render proposed intersection adaptations in both 2D and 3D, would feel familiar and accessible to most practitioners, was relatively easy to learn, and did not require extraordinary computing power. A graduate student vetted several off-the-shelf visualization tools, and reported back on ease of use and on quality and relevance of output for our purposes, recommending SketchUp as best when all features were considered. Practitioners whom we queried affirmed that the 3D design tool SketchUp best fit these criteria.

After using SketchUp to visualize five intersections in three North Carolina cities (small, mid-size, and large), we explored traveler perceptions of the intersections using a survey offered in two different formats—intercept and online, then adapted to a hybrid format in response to a pilot. The survey intended to highlight the traveler experience, and complement key informant interviews conducted with several dozen transportation professionals in CAV-forward cities.

Visual Tools in Research

Using tools—from simple sketches and models to sophisticated technology for dynamic visualization—to depict how humans interact with built and engineered systems has long been part of the planning profession, and nowhere more so than in transportation planning. Nearly two decades ago, Hughes (2004) described the visualization technology used for context-sensitive design and public engagement as experiencing a shift away from depicting how facilities *look* to how they *operate*, in the process requiring integration of modeling and simulation, and linking design and planning functions. Andrienko et al. (2017) noted that even sophisticated technology ties into human traits: “The science of visual analytics is continuing to develop principles, methods, and tools to enable synergistic work between humans and computers through interactive visual interfaces. Such interfaces support the unique capabilities of humans (such as the flexible application of prior knowledge and experiences, creative thinking, and insight) and couple these abilities with machines' computational strengths, enabling the generation of new knowledge from large and complex data."

Kasraian et al. (2021) used dynamic 3D street visualizations embedded in a stated preference survey (n=600) to quantify the perceptions of pedestrians using virtual streets and to explore trade-offs among competing uses for space. They found pedestrians preferred streets with transit mixed in (rather than cars alone), bicycle lanes along the curb, and sidewalk trees. Some studies have used headset tracking and videotaping of movement to explore pedestrian perceptions and preferences relating to AVs (e.g., Deb et al., 2020).

Coding and analysis of video often are used for researching travel behavior, such as greenway use (Bias et al., 2021; Christiana et al., 2022), bicycle facilities (Krizek et al., 2007; Monsere et al., 2015), and designs for mixing bicycles with motorized vehicles (Müggenburg et al., 2022). Video clips in an online format were used to survey over 3,000 students, faculty and staff at the University of California—Davis about bicycling conditions and perceived rider comfort (Fitch et al., 2022), with implications for infrastructure design and strategies to encourage and support cycling. Despite some variation in video ratings by socio-demographics and attitudes, there was "relative agreement about which videos are most comfortable and uncomfortable across our sample population segments," specifically bicycle infrastructure and low-speed roads.

Mukherjee and Mitra (2019) studied pedestrian compliance with signalization at intersections, using both videography and perception surveys, to generate actionable findings about design and operation features as well as personal attributes that correlate with signal violations. Xiang et al. (2021) combined off-site surveys using photos and virtual reality (VR) with on-site surveys in urban green space, to assess the reliability and validity of visual tools to understand perceptions and preferences. They found VR to be more consistent with on-site survey results than photos; preferred types of green space varied by season and by the visual approaches employed.

Objectives and research questions

The objectives of this study were to identify and describe CAV-readiness strategies used or proposed by CAV-innovator cities that may be applied locally by other locales, and empirically assess their potential safety and mobility impacts for people when they are not in vehicles, across various geographic and sociodemographic contexts. The overarching aim was to generate and share timely, accessible, evidence-based guidance with transportation professionals who are seeking to develop CAV-readiness strategies that also protect non-motorized travelers. We focused on infrastructure and policy measures adopted by transportation professionals at the municipal level, framed as four progressive and interlinked research questions to help guide North Carolina's local and transportation agencies in preparing for CAVs.

- What CAV-readiness initiatives are local agencies considering or pursuing, why, and in what contexts?
- How would those initiatives alter the physical design and operation of urban intersections?
- How would design and operational changes to urban intersections affect travel behavior, safety, and mobility of users of non-motorized travel modes?
- How would travel behavior, safety, and mobility impacts for users of non-motorized travel modes vary across physical and sociodemographic contexts?

We addressed these research questions in two phases. Phase I focused on identifying the CAV-readiness initiatives under consideration by local agencies and how common considerations may lead to changes to physical design and operation of urban intersections. In Phase II, we initially intended to translate those changes into hypothetical redesigns of real-world intersections and evaluating their likely impacts on non-motorized travelers through a visualization-supported survey. However, our Phase I research revealed that while local and state experts are frequently aware of and in many cases concerned about the potential need to upgrade infrastructure to pre-empt conflicts between CAVs and non-motorized road users, our initial hypothesis—that they were already developing strategies to do so—was not supported. Thus, Phase II pivoted to using theory to advance—and attempt to evaluate via public engagement in the form of intercept surveys of pedestrians crossing our studied intersections—potential strategies that may aid local professionals in their efforts to understand and prepare for CAVs.

Phase I: Identifying potential CAV-readiness strategies with implications for intersection design

Phase I focused on identifying and describing the ways in which local officials, state officials, and CAV professionals were discussing the infrastructure needs of CAVs, potential strategies to pre-emptively accommodate those needs, and implications of those strategies on the physical design and operation of urban intersections.

Methods

Qualitative data on CAV-readiness strategies provided the source content for our work in Phase I. We used thematic analysis of literature, documents, and interviews in order to identify common themes, concerns, and strategies relating to CAV-readiness. This supported additional goals of identifying, describing, and translating municipal CAV-readiness strategies for public and professional audiences, and communicating likely impacts of infrastructure redesign.

In several ‘CAV innovator cities’ with policies or active programs to support testing and deployment of CAV-readiness measures, key informants shared their expertise and insights. This was grounded in a small but growing body of literature on CAV-oriented infrastructure design and expertise in city-facing advisory organizations such as the National Association of City Transportation Officials (NACTO) and the National League of Cities.

In 2020, a team of 10 upper-level undergraduates in an applied Planning studio developed a systematic way to identify CAV-innovator cities, recruit key informants, and write interview questions.

Identify candidate ‘innovator’ cities and interview participants

We identified possible sites by scanning media and white/gray literature on CAV testing and pilot programs, reviewing the legislation and policies of their home states, and querying attendees at several conferences (e.g., the Transportation Research Board, Automated Vehicles Symposium). Tools such as TRID and academic research databases were useful for deeper probing of cities identified as active in this domain.

To identify and vet cities that meet the needs of the research design, the studio team developed a working definition of CAV-innovator cities (based on published plans, policies, programs, and partnerships) and from that created a rubric (Appendix A) to compare candidate cities, generating a list of 40 cities to research further. Those cities, vetted and considered for ease of study and relevance to the project, as well as geographic and sociodemographic variation, were triaged into a set of two dozen cities from which to recruit key informants.

Recruit interview participants

The process of identifying appropriate and accessible subject experts (key informants) took into account the agency or organization of interest, and the professional role within that body of individuals to recruit for interviews. Professionals were sought in transportation and land use planning, engineering, and technology sectors. Here too, a rubric was useful for searching, using 26 terms that fell in five categories: policy, public, private, partnerships, and miscellaneous. To avoid miscommunications, two team members (out of ten) were tapped to manage communications and active recruiting, using a spreadsheet to log inquiries and responses, and managing scheduling and assignments. We used a snowball technique of professional referrals—both at the recruiting stage, and as a wrap-up to completed interviews.

Develop interview instrument

The same planning studio produced a third major product: a draft semi-structured interview instrument. They drafted questions that addressed the research goal (probing the knowledge and insights of key informants in CAV-innovator cities). The rubric developed for this step (Appendix B) took into account the methodological literature and best practices in qualitative data collection, which were used to justify and characterize each question proposed for the interview instrument. After piloting with transportation professionals, they revised the instrument, with a written explanation of revisions.

Conduct interviews

Our recruitment process yielded a sample of 36 key informants interviewed in 15 cities across 12 states. Although the project was determined to be IRB-exempt (HS-23-119, Appalachian State University), we followed IRB-approved best practices in all aspects of interviewing: CITI-certified team members used standardized scripts to recruit and communicate with interviewees; the interview instrument included informed consent elements; and data were deidentified, then stored on computers of co-PIs in access-limited offices. The interviews were conducted online, with two team members, and recorded as audio files, which were transcribed into text files with the Otter.ai voice-to-text transcription tool. In the process of cleaning the transcripts (with careful reading and editing of obvious transcription errors), major themes were noted and used to construct an initial theme/code structure. Cleaned transcripts loaded into an Atlas.ti (version 8.4; atlasti.com) created a 'bundle' for content analysis. The analysts used an inductive/deductive strategy of coding text with established codes, and free-coding by adding new codes as needed. Atlas.ti tools such as frequency counts, code co-occurrences, and word clouds illustrated the prevalence of major themes and concepts, and the relationships among them.

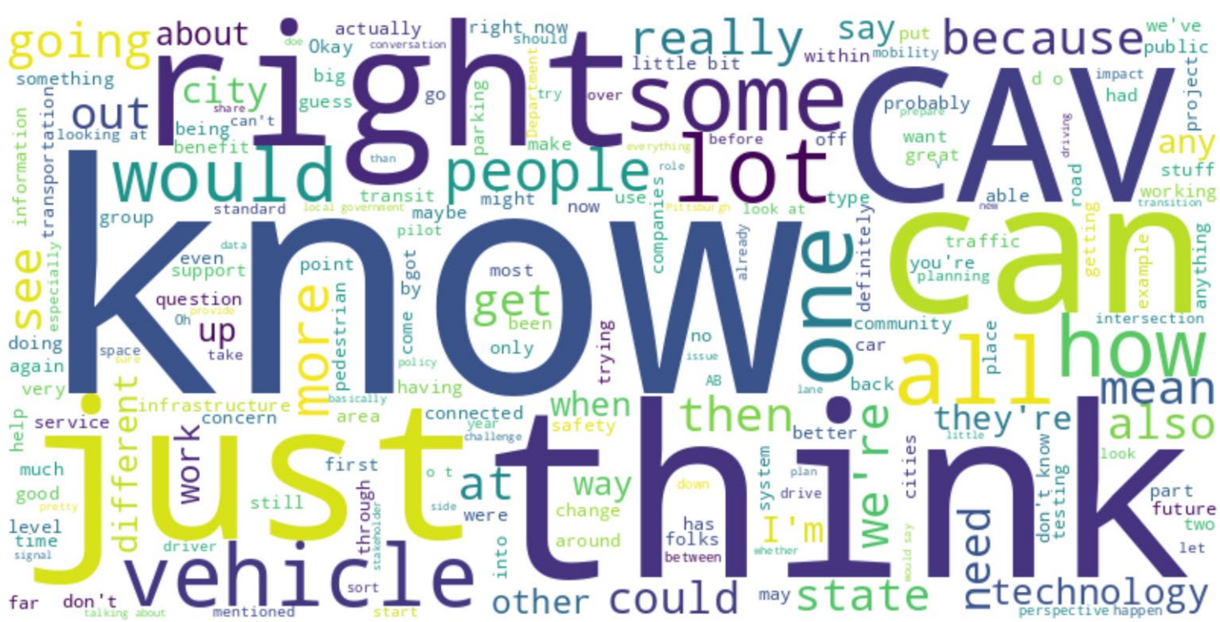

Figure 3. Example word cloud of the most common words from the interviews

Results

The results presented here include, first, a narrative summary of a review of documents and policies in cities where we interviewed key informants, and then a summary of the results from content analysis of interview transcripts, which are presented in greater depth in a paper prepared for peer review.

Policy and program review

We interviewed 36 experts in 15 cities, from 12 states plus the District of Columbia. The 15 cities are Austin, Boston, Charleston, Columbus, Jacksonville, Marysville OH, Memphis, Minneapolis, Pittsburgh, Portland, Raleigh, Reno, Seattle, Tampa, and Washington DC. In seven of the 12 states (FL, MA, MN, NC, OH, TN, WA), we interviewed DOT officials, as well as one or more municipal experts. We also interviewed a DOT official in Washington DC.

The states differ in the number, content, and focus of CAV-relevant legislation, with state bills covering safety, technology, liability, funding, planning, agency responsibility and oversight, and more. The states with the most identified bills—enacted or pending—at the time of the scan were California, Florida, and Massachusetts. California has 2017 legislation that authorizes an automated vehicle demonstration project, as well as legislation from 2018 addressing licensing and registering AVs, funding AV infrastructure, and allowing taxing of AV rides that may incentivize zero-emission vehicles. Legislation from 2019 establishes a California Council on the Future of Transportation to advise the Governor and Legislature on policy that will keep California at the forefront of automated and connected vehicle technology. The legislation also adopts language on vehicle controls and enforcement that recognize how CAVs differ from conventional vehicles.

Florida legislation from 2019 defines and describes CAV technology, addresses liability and innovation, designates strategic corridors, and supports programs like the Jacksonville Transportation Authority's Ultimate Urban Circulator; it also amends codes to recognize commercial AV platooning and safe-distance following vehicle behavior.

Massachusetts had (at the time of the scan) multiple pending state bills that define and describe CAVs and associated technology, and call for safe CAV integration into the Commonwealth's transportation systems in ways that enhance mobility, reduce emissions, and promote economic development, with standards for development and deployment of level-3 automation and above. One bill calls for all autonomous capability to be electric zero-emission vehicles. Other legislation addresses data needs, privacy, and articulation of CAVs with the Internet of Things.

Other states we studied have fewer bills in process or enacted—even if they have active vigorous CAV programs under way in one or more cities. Minnesota has a bill enacted in 2019 that allocates funds for several key agencies involved with CAV development, including the MnDOT, Metropolitan Council, and Department of public safety; the bill also establishes a new system for licensing and registration, and creates committees and task forces for oversight.

North Carolina enacted two bills in 2017 that amend the state code on safe following distance to recognize commercial automated vehicles in platoons that need exemption in some cases, establish regulations for fully automated vehicles operated on public highways, and create a committee on fully autonomous vehicles. In 2018, Ohio introduced two state bills, to create a state Council on Transportation Technology, and to set operational requirements for commercial AVs. Pennsylvania enacted a bill in 2018 that amends statutes and sets new rules of the road (such as platooning) that relate to highly automated vehicles, while South Carolina passed a bill in 2017 that amends the state code relating to safe following distance and the designation of an ‘operator’ rather than ‘driver.’

Two bills enacted by Tennessee in 2017 likewise address platooning and AV operation on public roads, with specified requirements such as notification to state agencies and insurance coverage. Two bills passed in the same year by Texas deal with braking systems in connected vehicles, and define AV technology, operator rights and responsibilities, and protocol for crashes in the state transportation code. Two Washington state bills enacted in 2018 appropriate funds and create an AV working group to develop policy recommendations, while a 2020 bill establishes minimum requirements for AV testing.

At the municipal level, policies and programs in several cities lay out the municipal CAV strategy in public-facing websites and documents. For example, Los Angeles has a well-populated website that links to earlier CAV policies and plans (such as Los Angeles, San Francisco, Austin, Portland, and Seattle), and shares their *Urban Mobility for a Digital Age* vision and *Blueprint for Autonomous Urbanism*. The site also links to research papers and technical reports for background context. Boston has a public-facing website that promotes ‘Boston’s vision for our transportation future’ in ambitious and compelling terms: “Zero deaths. Zero injuries. Zero disparities. Zero emissions. Zero stress.” The site contains protocols for phased AV testing and rollouts, and links with two current industry partners: Motional, and Optimus Ride—an MIT spin-off that tests operations, safety, and transit.

In Minneapolis, the strategic plan details a strategy for Automatic Vehicle Management control across the city’s fleets. Minnesota DOT also has a publicly posted state CAV strategic plan that introduces CAVs, discusses state policy and vision, describes the planning process, and offers recommendations. More generally, the state DOT website describes CAVs and their associated technology, describes industry and community partners, and articulates the potential benefits in terms of safety, equity, mobility, efficiency, and economic development.

The DriveOhio initiative has four municipal partners: Athens (a small college city in southeastern Ohio), Columbus (the state capital in central Ohio), Dublin (a Columbus suburb), and Marysville (a small city in central Ohio). Ohio is also home to the SmartColumbus advanced technology initiative, which has a deep public-facing web presence that promotes electric vehicles, details a safety plan for self-driving shuttles, provides mobility assistance and support for special populations, supports multimodal and integrated planning, assists in event planning, and more.

Pennsylvania has an AV task force whose members include municipalities, state and federal agencies, universities, business, labor unions, and non-profits. At the municipal level, Pittsburgh has a website for their Department of Mobility and Infrastructure, detailing objectives for safe testing, and their self-proclaimed first-in-the-world municipal principles for AVs, including a framework for communications and reporting for the city and their partners, and a vision that promotes low-cost low emissions and high-occupancy AV technology, with strong community-industry collaboration. Pittsburgh also has a non-profit organization, Pittsburghers for Public Transit, that has released a document to ‘chart a new course for urban mobility’ and analyzes CAV benefits in terms of affordable mobility for all, broad access to jobs in the transportation sector, and healthy safe inclusive communities, calling for investments in equity and a focus on results.

In Texas, Austin has a public-facing *Smart Mobility Roadmap* website that references the '3 revolutions'—the convergence of electric, autonomous, and shared vehicles, calling the latter (shared mobility) the 'biggest game changer' because it supports travel options without the need to own a vehicle. The *Roadmap* calls for a comprehensive strategy to deliver good service at low cost, high efficiency and accessibility, and lower congestion and pollution. They note that Google chose Austin as their second city, after the home base in Mountainview CA.

Not every state with legislation on the books has an active CAV program, and not all states with CAV activity have extensive legislation in place. Likewise, we found no direct correlation between a city's level of engagement and activity in the CAV realm and their public-facing documents and materials. At the same time, for those cities and states where we secured interviews with subject experts, state legislation and programs and municipal websites and documents may inform analysis of interview data.

Discussion

Interviews revealed deep interest in the prospect of CAVs in the future mode mix (CAVs and conventional vehicles, micromobility, pedestrians, cyclists), paired with a lack of specific knowledge on how to prepare for this on the part of some key informants. The general sentiment expressed by municipal leaders was concern about how to meet the needs of CAVs, along with a recognition of the likely need for future intersection design upgrades.

Many informants discussed how their agencies are thinking about modifying physical infrastructure like roads, signs, and signals to better support CAVs. For example, a project engineer from a midwestern state's DOT mentioned the importance of improving visibility of pavement markings:

> *"… the cars need to see lines all the way through intersections. So, as they get actually into the physical intersections, or say, for example, cross-street, and it's a normal four-way-type intersection. Typically, in the middle of that intersection, there are no pavement marks; humans can figure that out, which way they want to go and turn in […], but machine vision can't. So, adding more pavement marks in those kinds of empty areas is important."*[1]

This sentiment was echoed by a traffic operations official in a southern state's DOT:

> *So yeah, I mean, there's things that we can do to help support CAV technology and at the intersection to help protect pedestrians. I mean you can think of other things as far as making sure you are providing appropriate crosswalk delineation, making sure the vehicles can clearly see the delineation between the stop bar and the crosswalk and other things that need to be there as well."*

The senior program manager with a DOT in a western state highlighted how physical designs that reduce intersection complexity could reduce the need for technological investments:

> *"For intersections, folks need to be thinking, what can you do that doesn't require technology first? If you're concerned about wrong way detection, you can use geometric things, and curbs, and you can shape the intersection to fix that before you go put in a*

[1] Informant quotes are edited lightly for clarity

> *wrong way detection system. And you can have a roundabout first approach, you can be thinking: How do I protect movements that are challenging?"*

Informants also mentioned changes to capture some of the anticipated efficiencies embedded in automated driving, such as this description of dedicated freight lanes from a senior DOT official working on freight and logistics in a southern state:

> *"In theory, you could have three lanes of traffic traveling in the space of two lanes, if we ever get to that day in which everything is moving connected—which will be out of my lifetime—then you could actually save a lot of money and in theory, you could also save a lot of maintenance expenses. For example, if you knew that was the case, then all trucks go in the middle lane. Let's say for example of that scenario, you build the middle lane with concrete, which has a life expectancy longer than asphalt, then you can really save some dollars in the long run as well. So I do think that there's so much potential there for safety, and also for reducing costs as we move forward."*

And from a program director in a midwestern state's DOT, who discussed opportunities for HOV lanes, but also focused on the need for physical separations in order to ensure the effectiveness of such facilities:

> *"There's a lot of conversation about urban land use and planning as well as rural land use and planning. We might have to design more walkable communities and transportation is a critical part of connectivity. So that means you might have to create and manage the lanes for automated vehicles, right? So protected lanes, kind of like our HOV lanes. We might have to build a barrier between automated vehicles and the rest of the traveling public and so too we might have to build barriers between pedestrians and the rest of the road users.*

CAVs' need for physical separation to ensure maximum efficiency is a cause for concern among many of the professionals we spoke with. This sentiment is exemplified by transportation planner with a southern MPO…

> *"I've seen proposals to restrict pedestrian access to the road to cross the street to prevent those kind of pedestrian CAV conflicts. And I think something like that would be a shame just because, you know, personally, I don't think that we should be adapting to the new technology so much as we figure out how to implement that new technology in a way that works best for us."*

…and also from a DOT official in a different southern state:

> *"Are we going back to the early days when we made jaywalking illegal simply because it's inconvenient for drivers? Are we going to grade-separate pedestrians to accelerate implementation of CAVs? Or are we going to really mix this up? Is the CAV going to have to pass some sort of suicidal test when it comes down to the occupant versus the pedestrian? That kind of thing."*

Some informants were able to point to potential physical design changes aimed at directly improving safety for people on foot or bicycle, or even—as discussed by a private sector tech consultant in a midwestern city—using the predictability and control of automated driving to prioritize safe movement of pedestrians and bicyclists over vehicles in urban areas:

“I think potentially with the full deployment of automation, it can give us a better chance to rethink an intersection in general, and put the pedestrian as the priority. Which might sound counterintuitive to a lot of it. But, you know, I do think pedestrians and walking should be, especially specifically in urban environments—they shouldn't be forgotten elsewhere—but they should be a priority in urban environments. And I think there's a chance to rethink that. You know, as far as other alignments mean, certainly connecting the signals, as we talked about, but it may require looking at the geometric alignment of the intersections, just to make sure that any vehicle sensors that are there don't run into challenges.”

The southern MPO’s transportation planner highlighted the potential to capitalize on CAVs’ ability to operate safely in narrower traffic lanes to reclaim road space for expanded sidewalks and bicycle facilities:

“Potentially, in the far future, we might be able to narrow lane widths and maybe take some of that space back for us—streetscape uses, medians, expanded sidewalks, that kind of thing, but that would be pretty far in the future.”

An emerging technology program director with a midwestern state DOT also discussed the ability to repurpose space, in this situation taking advantage of reduced parking needs by CAVs:

“[T]here's a lot of different conversations about how parking might in fact become obsolete. Because long in the future when we’re retired and dead and gone, these [CAV] vehicles will not need to park and they’ll drive themselves. So there's a concept called Ghost Cars, where there might not be any people in them because the cars [are] able to drive around constantly looking; structures will actually go and fade into history. And we might be able to repurpose large parking facilities parking lots and reuse that space for the community.”

A representative from a midwestern transportation technology non-profit pushed this notion further, suggesting that CAV traffic could be effectively limited from urban centers:

“I would hope that maybe more parking locations or traffic flow can be directed outside of city centers [with CAVs]. Since you know, there won't be as much impatience, hopefully from the those behind the wheel, that the vehicles might be able to take a different route so that the city centers can really be places for greater walkability and coming together of people and experiences. And then vehicle parking, mass parking facilities could be outside the city as well.”

A few informants were optimistic that CAVs would expand mobility to underserved populations, both as first/last mile solutions to support public transit, and by providing direct service to people who are unable to drive:

“I think the most [likely beneficiaries of CAVs] would be those who are transit dependent or don't own a vehicle or have lower per household vehicle ownership, as well as folks in the disabled community who are not able to drive cars themselves, who would be able to take advantage of CAVs”

“One thing we’ve seen is a couple of research projects looking at how CAVs might be used to provide paratransit assistance to the elderly and disabled, and that would be a huge win in terms of mobility for those populations. Generally, anyone under-age, with

vision or other impairments, all those groups would benefit from having more access to a vehicle. Potentially transit services in general might be automated, which would lead to cost savings and add more services potentially. Businesses might be able to look into deliver goods more efficiently."

The latter informant, a transportation planner with a southern MPO, went on, however, to express concern over deleterious impacts on mobility driven by CAVs' potential to exacerbate urban sprawl:

"Now the big question, of course, is land use and how CAVs will impact that. It seems likely that they could drive urban sprawl and drive people further outside of the city center. As you know, the cost of commuting is felt less in a CAV. But perhaps, you know, network effects from the TNCs will drive people inwards."

Finally, the emerging technology program director for a midwestern state DOT brought up the equity implications of computer vision algorithms that frequently fail to accurately identify pedestrians of color:

"Artificial intelligence is being designed that's not being developed by developers and software engineers of all backgrounds, which means it's actually building in discrimination biases into the systems. An example of that is facial recognition. Right now it may be able to see a white face like mine. I am a white, female and identify as such. But it actually has trouble identifying features of color and black women."

The transportation planner from the southern MPO also touched on software shortcomings, using the much-publicized death of Elaine Herzberg as an example:

"The biggest concern around CAVs would be the impacts on pedestrians and other motorized road users. We saw a couple years ago the death in Arizona because the Uber CAV couldn't recognize a pedestrian walking through the roadway. And we already have a high rate of pedestrian fatalities here so we don't want to see that go up any further because the software just isn't ready."

These concerns underscore the challenges with relying solely on technological solutions to ensuring safety for people on foot or bicycle, and supports this project's premise that technological innovation should be both supported and bounded by appropriate physical designs.

When pushed to explain what physical design changes were under consideration, few informants were able to pinpoint specific ideas. Indeed, many of them looked to the interview team for thoughts, asking questions about what other cities in the study were considering. In the absence of such guidance, many interviewees fell back to general principles of pedestrian- and bicycle-friendly design, such as high visibility pedestrian crossings, tighter turning radii, elimination of challenging or complex movements, and installation of pedestrian refuge islands, medians, expanded sidewalks, and protected, dedicated cycling routes that continue through the intersection.

Finally, we asked these professionals for their thoughts on the biggest barriers to implementing the changes needed to ensure safe, convenient access and mobility for pedestrians and bicyclists in a CAV-prevalent landscape. Lack of funding for widespread infrastructure upgrades was a common and expected theme, which some informants, including this CAV researcher from a midwestern think tank, linked to the uncertainty over realistic timelines for CAV deployment:

> *"I think I was a little naive as to how quickly things can change, particularly infrastructure and cities and how long term transportation plans are. So I used to be more optimistic that that I think cities would change quickly once CAVs became more widespread, which granted is minimum 15 years, I think, but I hope that we can repurpose some of the public space that maybe won't be as necessary or utilized when and if CAVs become more widespread. That being said, I've now come to have a much more clear understanding of how difficult that kind of is for various reasons, whether it's legislative, whether it's budgetary, just having the resources at the city level to change how our cities look. I think there will be opportunities to change, to expand pedestrian space and bike lanes, because these CAVs can more easily stay in more narrow lanes [compared to human-driven cars]. I hope cities can find the resources to do that and give back some space to the residents."*

Others noted the lack of consistent standards, best practices, or transparency among CAV technology developers as a substantial barrier, as explained by the emerging technology program director with a midwestern state DOT:

> *"I have concerns not in the technology. I have concerns about how the industry will deploy it and its development. […] The industry is not [as] forthcoming as the public sector would hope them to be. Because, they're driven by shares, revenues, and the purchase of automobile sales. And so, they have an interest in keeping their secrets trade secrets to gain a competitive advantage. The problem is that they're making claims. For example, just last week, Elon musk of Tesla announced that level 5 self-driving vehicles will be on the roads at the end of the year. That is impossible; that will not happen. And so, the public is being misled and confused."*

But we also heard frustration with the transportation profession's historical prioritization of vehicle throughput over safety and mobility, particularly for those outside the vehicle, exemplified by this statement from a DOT official in a southeastern state:

> *"I'm afraid that when you put the business aspect of CAVs in there with a lot of other stuff, you'll get back into undoing a lot of the past 20 years' worth of emphasis on pedestrianization and bicycles and, and complete streets and all that kind of stuff. It could be completely undone by the claim that it's going to hinder implementation of CAVs."*

The same official also lamented reliance on conventional data to identify infrastructure in need of upgrading, making the case for universal, system pedestrian and bicycle safety improvements instead:

> *"I think [CAV developers] need to clarify what it is they're trying to accomplish. And, you know, safety was one of the original goals. But then how do you define safety? If you go by statistics, an intersection so dangerous to pedestrians it would be suicidal to cross is going to be listed as very safe because nobody will attempt to cross it. So the crash rate there is close to zero, although everybody who does attempt to cross it is likely to get hit."*

Finally, we heard expressions of resentment about the use of automation as a safety solution, sacrificing future employment opportunities rather than focusing on proven approaches to addressing safety today:

> *“We decided maybe this [automated shuttle] could be a cool pilot and you know, also the vehicles have cameras sensors and are operated at a very slow speed and never go over that speed and that would arguably be safer to put alongside pedestrians and bicyclists. [Residents of a low-resource community and transportation advocates] strongly came out against that shuttle being autonomous for a few reasons: Are they taking jobs away from drivers? Residents, understandably so, are very frustrated or concerned that we are seemingly prioritizing this new technology rather than addressing some of the problems and hurdles they faced for a long time now and [wanting us to try] to solve the now problems rather than looking to future testing and development of this new technology.”*

The absence of a body of empirical evidence to guide intersection redesign leaves a gap filled by theory, which informs work addressing research question 2. For example, if CAVs can operate more space-efficiently (requiring less road space than conventional vehicles) and more effectively if not intermingling with other modes, then road space liberated by increasing CAV mode share could be repurposed for separate, protected infrastructure for other modes. At the same time, such a shift in right-of-way allocation raises the danger of incompletely connected and inadequate facilities for non-motorized travelers concomitant with increasingly specialized and restrictive space for CAVs, which could exacerbate existing inequities in mobility across modes and travelers.

Phase II

In Phase II, we initially intended to translate the strategies identified in Phase I into hypothetical redesigns of real-world intersections, and then evaluate the likely impacts of those redesigns on non-motorized travelers through a visualization-supported survey. However, our Phase I research revealed that while local and state experts are frequently aware of and in many cases concerned about the potential need to upgrade infrastructure to pre-empt conflicts between CAVs and non-motorized road users, our initial hypothesis—that they were already developing strategies to do so—was not supported. Rather, Phase I uncovered both optimism and concerns over how pedestrians, bicyclists, and other non-driving road users might fare, along with a general unease over the lack of clear guidance or standards for ensuring that all road users are accommodated during and after the transition to a CAV-dominant vehicle fleet. Thus, Phase II pivoted to using theory to propose potential strategies that should simultaneously support the projected operational needs of CAVs and provide for safe, comfortable, convenient mobility for people when they are not in cars. Our review and evaluations of those strategies supported recommendations to aid local professionals in their efforts to understand and prepare for CAVs.

This phase of the research involved several steps:

1. Identifying potential strategies to simultaneously support the projected operational needs of CAVs and provide for safe, comfortable, convenient mobility for people when they are not in cars,
2. Translating those strategies into hypothetical redesigns of a sample of existing urban intersections in North Carolina cities,
3. Rendering the existing and redesigned intersections in a 3D visualization, and
4. Surveying pedestrians familiar with the intersections about their current experience with the intersection, their thoughts about the impacts of CAVs on their intersection experience, and their perspectives about how the proposed design changes would affect their perceptions of safety, comfort, and convenience.

Methods

Developing design standards for CAV-adapted urban intersections

As explained previously, we turned to theory to support our development of strategies to guide CAV-adapted intersection upgrades in the absence of local-level innovation. The projected CAV operational needs (predictability, separation of modes in busy or high-speed contexts, clear signage and pathfinding aids) and best practices for safe, comfortable, and—importantly—separate facilities for pedestrians, bicyclists, and other users of non-vehicle travel modes, suggests using principles of protected intersections to guide our CAV-adapted intersection upgrades.

Next, we established a set of guiding principles to redesign our study intersections based on the joint needs for predictability and separation by CAVs and the Dutch protected intersection model. Our central parameters were that the designs must provide safe, comfortable, convenient mobility regardless of mode, without need for additional enforcement or modal exclusion, and—recognizing time, space, and fiscal limitations—must fit within existing roadway footprints. In order to stay within those parameters, we established the following guiding principles:

Safety
If pedestrians, cyclists, and other non-motorized road users do not perceive a design as safe, they are unlikely to use it. Thus, the design must first and foremost ensure the safety—both perceived and actual—for these users. We used a sustainable safety (aka safe system) approach to achieve this principle:

1. Minimize risk of serious collision: Routes for pedestrians, cyclists, and others not in cars must minimize the risk of collision between modes through physical protection and spatial separation and reduced time spent in conflict areas. This principle was expressed with bulb-outs and raised islands, physical barriers in waiting/queuing areas, orienting pedestrian and bicycle crossings at right angles to curbs, and reducing and narrowing travel lanes.
2. Minimize likelihood of serious collision: Where the risk of collision cannot be eliminated, the likelihood of collision must be minimized through improved visibility and temporal separation. This principle was supported with bulb-outs and raised islands, raised crossings, orientation of motor vehicle traffic so that it meets crossings at right angles, and exclusive or leading signal phases for pedestrians and cyclists.
3. Minimize severity of collisions when they occur: Where the likelihood of collision cannot be eliminated, the severity of potential collisions must be minimized through reductions in vehicle speed. For CAVs, this principle was upheld through operational controls. For human-driven vehicles, it was supported through traffic calming interventions such as tightened turning radii and raised crossings.

Accessibility and navigability
Intersection designs must ensure accessibility for all people, including those with physical or cognitive impairments (including temporal impairments such as intoxication or fatigue), those who are unfamiliar with the design, those who are unfamiliar with social norms around road use in the context in which they are situated, and those who lack experience navigating in traffic, such as children. In addition to conforming to federal ADA regulations, our designs borrowed elements from the concept of Self-Explaining Roadways, which call for the use of direct, intuitive routes, simple and minimal signage, and standardized materials. Where travelers must use judgment to determine when to enter a conflict zone (such as a crosswalk), the design ensures that only one potential conflict is presented at a time, further minimizing cognitive burdens on the road users. Furthermore, conflict zones should be clearly demarcated to indicate that faster modes should reduce speeds to match and yield to slower modes.

Comfort and convenience
Pedestrian and bicycle routes should be designed to minimize travel distances, wait times, exposure to pollution (including air and noise pollution), and exposure to non-traffic-related hazards (such as direct sun). They should also provide ample lighting and options and escape routes in case the user needs to get away from threats to their personal safety or security. While such features may be viewed as important amenities, they are also a means to encourage use of the intended facilities, and thus reduce the likelihood pedestrians, cyclists, and other people not in cars will opt to step into traffic and potentially interfere with CAV operations. As has been suggested in the literature, once people gain trust in CAVs' programming to always stop for humans in the street, pedestrians and bicyclists may become less willing to put up with separate facilities that are uncomfortable or inconvenient. Compliance with intended routes should be maximized not through enforcement or physical barriers, as these approaches introduce

challenges to mobility, justice, and personal safety, but by providing routes that are clearly superior alternatives to traveling in the roadway. Our redesigned facilities sought to identify routes that minimize overall crossing distances and wait times, provide protected waiting areas set back from high speed or high-volume traffic, and do not channelize users into spaces that lack escape routes.

Congestion

The operational efficiencies expected from CAVs will make it possible to convert some existing road space into the separated facilities for pedestrians and cyclists described above. Nevertheless, CAVs will still need room to queue while waiting for other traffic—vehicular and not—to clear conflict zones. Thus, our redesigns retained left turn lanes and set pedestrian and bicycle crossings back from intersections to provide clear zones for at least one car to wait, out of the way of other vehicular traffic, for these crossings to clear before entering them.

Many urban intersections will also need to allow navigation by larger freight vehicles and emergency vehicles. Our designs thus employed flex-posts and mountable curbs, with hardened barriers set back away from turning vehicles. In-street bike paths were separated via low curbs or flex-posts and were designed such that they can be used as emergency pull-outs (to clear travel lanes for emergency vehicles) if necessary.

Space for transit

As discussed in the literature review, there is no consensus on whether demand for public transit will diminish or expand in a CAV-dominant future. Our designs took note of existing transit facilities, stops, and routes, and retained existing location for vehicles to stop and embark/disembark passengers. Where possible, we sought to minimize potential conflict between transit vehicles and CAVs, and between transit passengers and people using bicycle paths or sidewalks. When there were opportunities to relocate bus stops to the far side of intersections along their designated routes (due to the reallocation of road space from general travel to separated pedestrian and bicycle facilities), we did so.

Identifying study intersections

In consultation with NCDOT and local transportation professionals, we identified six intersections in North Carolina in which to test our CAV-adapted protected intersection designs. These intersections—two each in Boone, Greensboro, and Charlotte—represent different urban environments with varying mode-mixing. Target intersections were signalized, with peak hour level of service (LOS) of D or worse on at least one approach, and with existing non-motorized facilities (e.g., sidewalks, marked crossings) and moderate foot traffic. The three cities of Boone, Greensboro, and Charlotte represent a small, mid-sized, and large city, respectively. In each of these three study sites, two selected existing intersections represent differ conditions for current pedestrians and different opportunities for future CAV-ready intersections that design in protections and prioritization for people who are not in vehicles. For example, the ‘Mellow Mushroom’ intersection on the west end of Boone’s downtown is relatively pedestrian-friendly, with the streets intersecting at 90 degrees, and relatively low levels of motorized traffic; by contrast, Boone’s ‘Wendy’s’ intersection is wide (6 or 7 lanes across), and extremely heavily traveled by auto traffic, with few pedestrian amenities. Ultimately, time constraints and technical difficulties limited our study in Charlotte to one intersection.

Translating CAV-adapted design standards to study intersections

CAV-adapted protected intersection principles in practice

Once we had the intersections identified, we documented their existing designs and geometries and then, using the redesign principles described above, came up with a draft plan for reallocating lane space and establishing separate, protected facilities for different modes on each leg of the intersection. For example, for the 'Wendy's' intersection in Boone, we proposed the following lane reconfigurations:

Table 2. Example proposed roadway reallocation, Boone-Wendy's Intersection

Intersection	Boone Wendy's	Overall plan:	Reduce general purpose lanes to 2 through lanes + left turn lane for all legs. Convert right turn lanes into protected; separate space for non-motorized modes. Add painted or raised medians on all legs.
Leg	**Width**	**Existing**	**Proposed**
Northwest	65'	*Inbound*: One L turn lane, two through lanes *Outbound*: Two through lanes; painted non-conforming bike lane	*Inbound*: 9' L turn lane, 10' inner through lane, 11' outer through lane; 6' bike lane, raised or protected with flex posts *Center*: 3' raised or painted median *Outbound*: 10' inner through lane, 11' outer through lane; 6' bike lane, raised or protected with flex posts
Southwest	81'	*Inbound*: Two L turn lanes, two through lanes, one R turn lane *Outbound*: Two through lanes	*Inbound*: 10' L turn lane, 11' inner through lane, 11' outer through lane; 8' in-street bike path, raised or protected with flex posts; use extra space between outer through lane and bike path as raised or painted buffer *Center*: 3' raised or painted median *Outbound*: 11' inner though lane, 11' outer through lane; 8' in-street bike path, raised or protected with flex posts; use extra space between outer through lane and bike path as raised or painted buffer
Southeast	69'	*Inbound*: Two L turn lanes, two through lanes *Outbound*: Two through lanes	*Inbound*: 10' L turn lane, 10' inner through lane, 11' outer through lane; 6' bike lane, raised or protected with flex posts; use extra space between outer through lane and bike path as raised or painted buffer *Center*: 3' raised or painted median *Outbound*: 10' inner through lane, 11' outer through lane; 6' bike lane, raised or protected with flex posts; use extra space between outer through lane and bike path as raised or painted buffer
Northeast	77'	*Inbound*: Two left turn lanes, two through lanes *Outbound*: Two through lanes	*Inbound*: 10' L turn lane, 11' inner though lane, 11' outer through lane; 8' in-street bike path, raised or protected with flex posts; use extra space between outer through lane and bike path as raised or painted buffer *Center*: 3' raised or painted median *Outbound*: 11' inner though lane, 11' outer through lane; 8' in-street bike path, raised or protected with flex posts; use extra space between outer through lane and bike path as raised or painted buffer

Next, we extended the bicycle facilities through the intersection. The routes for these crossings conformed to the CAV-adapted protection intersection principles: minimize crossing distances; orient crossings at 90 degrees to vehicle traffic and curb; ensure space for one vehicle to wait, after turning, before intersecting the crossing; and minimize deviation from straight line travel as much as possible. (In Fig 3b, below, the in-street bicycle facilities are painted green, with brighter green signifying elevation to curb level.)

We then added in pedestrian crossings adjacent to and behind the bicycle crossings, following the same principles as described for bicycles. Pedestrian crossings are shown in bright blue below (Fig 3c), but in reality would be painted as standard zebra crossings. Note that the pedestrian crossing supersedes the bicycle crossing where they conflict, in keeping with the principle that faster modes should yield to slower modes wherever possible. Like the bicycle crossings, the pedestrian crossings are also raised.

Fig 3c also shows new lane striping, delineating traffic lanes as described above. In this sketch, the 3' medians are painted, rather than raised. Raised medians are typically regarded as safer and more comfortable for pedestrians and cyclists for at-grade crossings, and are less critical (though still welcome) for raised crossings. Note that the medians extend farther into the intersection than the centerlines do in the current configuration, in order to visually tighten turning radii and reinforce waiting space for cars.

Finally, we added protection to the design (Fig 3d). Because of the size and traffic speeds and volumes at this intersection, we propose concrete bulb-outs to further tighten turning radii and provide additional space and comfort to pedestrians and cyclists waiting to cross. These bulb-outs can be made with mountable curbs if necessary.

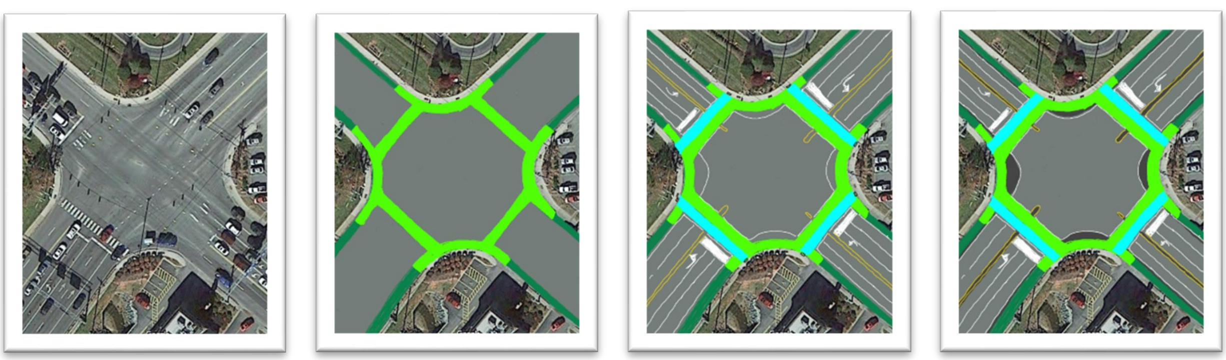

Figure 4. Sketches showing example redesign progression

Visualizing the CAV-adapted protected intersection designs

Lastly, we rendered the existing conditions and proposed redesigns for each intersection in 3D using SketchUp[2] to enable visualization-supported public engagement. 3D visualizations can effectively and quickly convey hypothetical design changes to the public and to decision-

2 The team employed a graduate student to test, critique, and recommend a visualization tool from among a set of accessible off-the-shelf visualization packages such as practicing planners or even the public might use. Based on a comparison of cost, availability, ease of use, and relevance output, the team adopted SketchUp as the tool for rendering the six selected intersections in 3D static and dynamic representations that are easily understood by transportation professionals and the general public alike.

makers, with the potential to improve public participation in transportation planning (as mandated by the 2009 federal transportation bill SAFETEA-LU).

The visualizations were drafted by graduate students well-versed in the CAV-adapted protection intersection principles. In addition to the basic intersection elements, the students also added in buildings, streetscape amenities, and people to create more realistic and aesthetically pleasing renderings. The team used an iterative process until all members of the team were satisfied with the final designs. The students then saved the renderings in both static form and as video ‘flyovers’ in order to give viewers an immersive sense of the feel and function of the hypothetical redesign.

Pedestrian surveys

In the final step of Phase II, we used the intersection visualizations as a tool to aid in learning from current users with experience traversing the study intersections as pedestrians how their perceptions of their safety, comfort, and convenience might change in a CAV-adapted environment. The survey, which was administered via Qualtrics, included questions on the user’s most recent experience walking through the intersection in its current configuration and about their familiarity and comfort with sharing spaces with CAVs. Survey participants were then shown a brief (~30 seconds) flyover video of the hypothesized redesign and/or a series of images of the rendering depicted from multiple angles, and asked questions about how their behaviors and perceptions might change if the new configuration were installed. The end of the survey asked a limited number of sociodemographic questions so that we could gauge the representativeness of our survey sample.

The survey component of this study, which was designed based on established methods for conventional face-to-face intercept surveys, encountered multiple and varied challenges. First, a pilot survey at a Boone intersection, with survey instruments loaded onto tablets, met strong resistance to participation from pedestrians and a severely limited response, and raised the question of selection bias (most non-white non-male passersby selected out). We switched to a card-handout approach, in which pedestrians were offered a card with a brief description of the survey and QR code and URL link to a web version of the survey, along with a modest incentive.

In consultation with local colleagues in each of the three study cities, the team identified days with likely heavy foot traffic at each intersection to distribute surveys. Members of the team then stood at each intersection for two hours on the chosen days, attempting to recruit everyone (or one person from each party) who passed them on foot or using an assistive mobility device. The team members held signs indicating that they were soliciting participants to take a survey on walking conditions at the intersection. Team members initiated contact by holding their sign so that pedestrians could clearly see it and asking, “Share your thoughts about walking at this intersection?” Any passerby who expressed interest was then offered a survey card. Team members also had tablets loaded with the survey in case passersby wanted to take the survey *in situ*. The surveyors use datasheets to record user counts in order to determine response rates and representativeness of the sample.

Due to unexpectedly low pedestrian activity and concomitant low response rates at the Boone and Greensboro intersections, the team decided to attempt to oversample these sites by conducting an additional round of survey distributions on a different weekday. The Charlotte site was dropped from the survey distribution, with all remaining survey resources reallocated into increasing response rates in Boone and Greensboro.

Results

Intersection visualizations

The team produced a series of still images and brief video fly-throughs of showing the proposed intersection redesigns in 3D. Figure 5 shows aerial views of the proposed redesigns alongside satellite imagery of each of the study intersections' existing conditions.

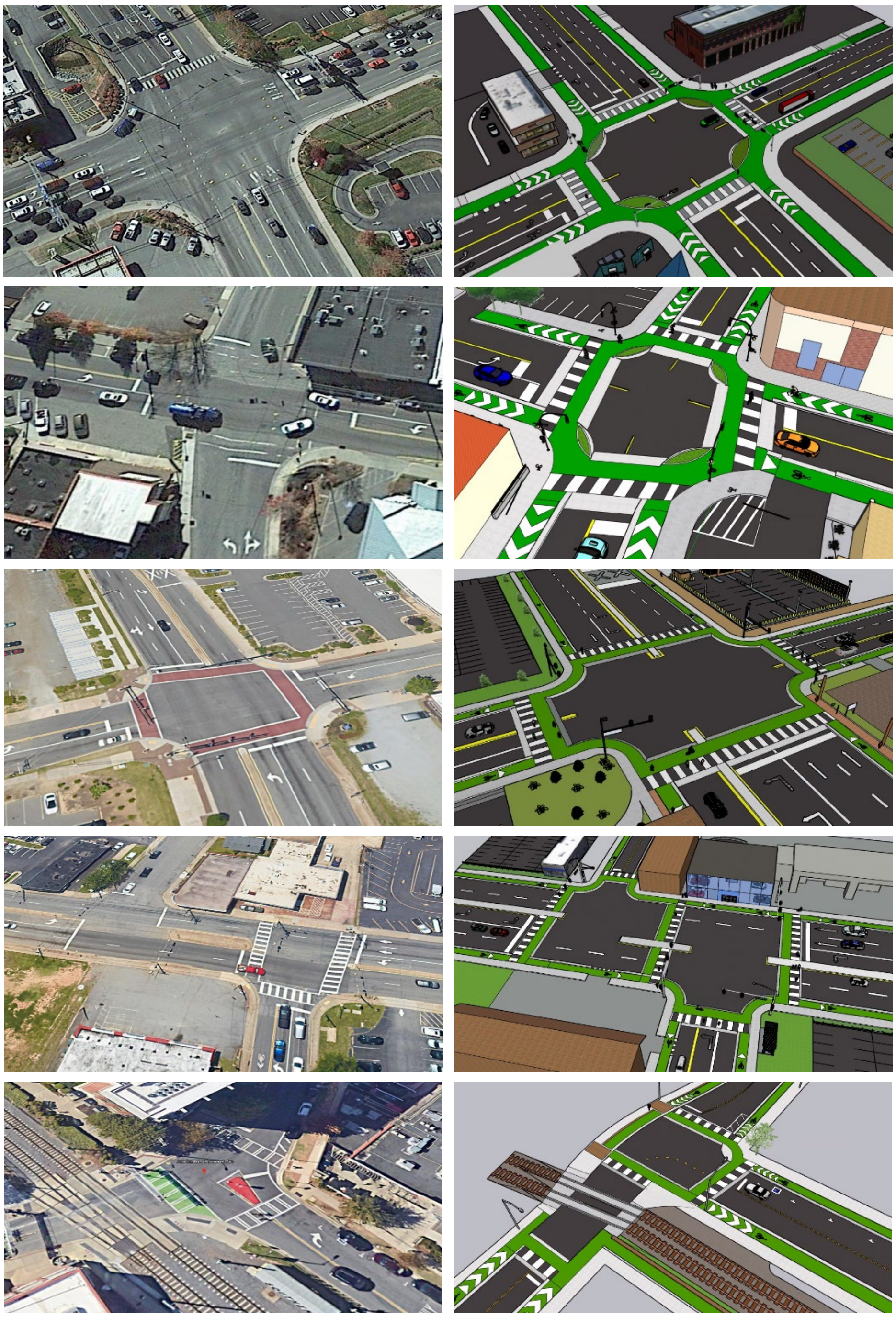

Figure 5. Study intersection aerial views: existing conditions and proposed CAV-adapted redesigns

Pedestrian survey

The revised survey format—oversampling at four sites using cards with QR codes and URLs, attached to a small incentive (granola bars and fruit snacks)—still failed to meet targets for participation and response, with very low incidence of pedestrians crossing the intersections, and nearly two thirds of pedestrians encountered refusing the card. We recorded only 20 responses across the four sites. Surprisingly, the Greensboro Elm St site yielded no responses at all, despite its location at the edge of a popular dining district, and despite having the second highest tally of pedestrians encountered and survey cards distributed. Survey distribution and response rates are shown in Table 3, below. The number of responses recorded fell far below the threshold for statistical analysis, so will not be analyzed here.

Table 3. Survey distribution and response rates

Site	Responses recorded	Day	Weather	Total pedestrians	Survey cards distributed
Boone Wendy's	2	Saturday	warm and sunny	1	0
		Monday	warm and sunny	1	0
Boone Mellow Mushroom	16	Saturday	warm and sunny	63	16
		Monday	warm and sunny	15	10
Greensboro Tate/Gate City	3	Saturday	hot and humid	4	2
		Thursday	hot and humid	5	0
Greensboro Elm/Gate City	0	Saturday	hot and humid	8	5
		Thursday	hot and humid	27	12
Total	20			124	45

Note: the number of recorded responses exceeds the number of cards distributed. This may be due to sharing of survey materials among respondents and/or respondents accessing the survey via the clipboard signs held by the research team members

Discussion

As explained previously, the analysis of interviews with transportation professionals (Phase I) did not yield guidance or even concrete ideas of ways in which the physical design of urban intersections is likely to evolve, either in preparation for or in response to the widescale introduction of CAVs. Some interviewees were able to highlight specific concerns—namely, that CAVs' need for predictability may lead to the installation of barriers to limit the movements of pedestrians, bicyclists, and other non-driving roadway users. Many others simply expressed a hope that the infrastructure of the future prioritizes safety and walkability over throughput, coupled with an optimism that automation technology will ease this shift in priorities.

The lack of concrete plans, and the interviewees' open desire for guidance and best practices for CAV-ready intersection design, led the research team to modify the original approach for Phase II. Rather than creating hypothetical intersection redesigns based on agencies' own plans—which the team learned were not as developed as had been hypothesized—we sought to identify existing intersection design guidance that comported with the hopes and mitigated the concerns expressed in the interviews with respect to safety and movement for pedestrians, bicyclists, and other non-driving roadway users. Informed both by the literature review and the team's research experience on safe system-aligned infrastructure design, we identified protected intersections as an established best practice that most closely fit the concerns and priorities expressed by the interviewees.

Adapting the study intersections to meet the principles of protected intersections was straightforward: reference materials to guide such conversions abound. The process was made easier by the projected spatial efficiencies of CAVs versus human-driven cars—CAVs are widely presumed to be able to operate safely in narrower lanes and to require fewer lanes before reaching critical congestion thresholds. Capitalizing on these efficiencies allowed us to gain space for protected intersection features by reallocating space within existing curbs. If the concerns expressed by our informants that CAVs will ultimately require complete separation of modes in order to operate efficiently pan out, then cities will need a cost-effective approach to intersection design that can be implemented on a massive scale. That CAVs' spatial efficiencies allow for implementation of protected intersections within existing roadway footprints will prove critical.

Rendering the intersection upgrades in an off-the-shelf, accessible, 3D-enabled software package that would produce visualizations suitable for public engagement proved to be more of a challenge than anticipated. At the start of this project, in early 2020, we scanned a large set of visualization tools, then narrowed the set to critically review a small set on several parameters, as detailed earlier. SketchUp—the package recommended to us by the transportation professionals we queried early in the study period—worked well for creating conceptual models that can be used to guide discussions among professionals familiar with the models' underlying principles. However, going from conceptual model to the realistic, immersive experience needed to adequately gauge public perceptions of the proposed designs was quite challenging. While this can be achieved in SketchUp, it is a laborious process that involves more skill than we would have liked for an off-the-shelf, accessible package.

During the course of this project several purpose-built tools for visualizing new intersection designs have emerged. A number of state DOTs have turned to consulting firms with dedicated visualization teams to build custom platforms. Artificial Intelligence (AI) tools burst onto public life—in schools and workplaces—and are being used for not only text for also visual and even audio tasks.

Nonetheless, SketchUp still has some distinct and important advantages: specifically, the platform is highly customizable and allows users to integrate their own graphics into visualizations. This allows for the creation of renderings that show infrastructure designs placed within the existing built environment. Existing landmarks, facades, signs, and backgrounds can all be brought into a SketchUp model, enhancing a viewer's ability to orient themselves within the visualization and providing a sense of familiarity and realism.

With the rapid gains in computer graphics technology, however, new platforms are likely to emerge that combine the flexibility and realism of SketchUp with the simplicity and accessibility of purpose-built programs, such as Remix (https://ridewithvia.com/solutions/remix/streets. While we recognize that the specific tool used and discussed here (SketchUp) may be superseded by new and emerging technology, that need not negate the general approach we advocate in trying to prepare for CAVs: Scan for CAV legislation and programs, talk to the transportation experts involved, represent intersections of local importance and interest, and seek to understand the experience of non-motorized travelers using those facilities—in both their current and possible future configurations.

Using SketchUp to create realistic visualizations for public engagement

Given the challenges the team faced using SketchUp to create realistic visualizations, the team developed a standalone practitioner's reference guide detailing the methods we used, in order to aid replication by others. The guide includes information on rendering existing conditions, modifying existing conditions into proposed new redesigns, integrating realistic imagery, and exporting the renderings into visualization tools for use in public engagement materials. This reference can be used to guide local and state transportation professionals challenged with developing CAV-readiness strategies that maintain and enhance safety and mobility for pedestrians, cyclists, and other non-vehicular roadway users while maximizing potential safety and efficiency benefits of CAVs.

Pedestrian survey

The difficulties experienced in reaching the targeted sample may represent a new 21st-century post-pandemic normal of skepticism, resistance to face-to-face interaction, and concern about ubiquitous surveillance—conditions that appeared to render established survey methods inadequate for our purposes. While the literature—for both research and practice—contains examples of new technology and techniques for reaching the traveling (particularly non-motorized) public, those that rely on apps and social media may miss some of the individuals of concern. The need remains for survey methods that are both accessible and welcoming in soliciting the firsthand views of a broad cross-section of travelers with varying levels of technology-comfort, *and* produce data sufficient in quantity and quality to support sound analysis that can inform policy and implementation.

Conclusions

This project began with a clear set of interlocking objectives, most of which were achieved. Those that were not generated unexpected new insights that in themselves may be useful additions to the evolving discussion about non-motorized travelers in a CAV-adapted world.

A review of the literature relating to technology adoption, non-motorized travel, design and policy for multi-modal facilities, and the automation of vehicles supported the design and deployment of interviews with dozens of transportation experts in CAV-forward cities, generating a body of qualitative data that is rich and layered, and reveals a depth of interest and concern about CAVs and their place in our transportation future. The primary theme to emerge from the interviews was that knowledgeable and committed transportation professionals expect CAVs to transform the landscape, but for the most part do not have a clearly articulated pathway for the steps that should be taken to support a smooth transition that protects all travelers and is sensitive to the built and natural environments. Experts commented thoughtfully, in some cases painfully, on how widespread appearance of CAVs may impact travelers of all modes, alter land use, and challenge the work of transportation professionals and governments—at local, regional, and state levels.

The interviews informed the second phase of the research, which focused on evaluating potential impacts of CAV-readiness adaptations on non-motorized travelers. In the absence of a clear set of steps recommended by the key informants we interviewed to prepare for CAVs, intersection visualization focused on 1) faithfully replicating the current conditions at five intersections in three North Carolina cities, then 2) creating future designs for those intersections that both accommodate CAVs and protect and support non-motorized travelers. Graduate students skilled in design used the off-the-shelf product SketchUp to visualize both current and future conditions at select intersections, which were then used in an intercept survey in the field.

Both processes (visualization and surveying) proved to be instructive in how changing conditions may demand a change in standard field practices. The visualization process was successful, insofar as it produced renderings of the intersections (both static and dynamic) that looked realistic and legible, yet may have been surpassed by newly available tools (including AI) that can produce similar results with less time and effort. The survey process likewise was instructive, producing very limited responses given the resources devoted. Moreover, the field experience of high refusal raises the question of whether in-person intercept surveys in a busy urban setting may be ineffective, particularly given widespread expectations of privacy, anonymity, and freedom from hassle and likely exacerbated by pandemic-era changes in attitudes about face-to-face interaction. Evolving survey methodology increasingly offers technology-assisted methods; however, even where apps and links may increase response rates, selection bias may be a concern, and for this study may mean that the very populations of greatest concern for impacts on mobility and safety could be underrepresented.

This mixed-methods look at preparing for CAVs in some innovator cities, combined with intersection visualization and traveler surveys, revealed deep interest in and concern about how cities and states should prepare for CAVs, a desire among transportation professionals for clearer information about the limitations of CAVs and necessary accommodations needed to mitigate those limitations, and a need for revised intersection design standards to ensure the mobility and safety of non-motorized travelers. The research also raised critical questions about how best to use field methods such as visualization and surveying to support transportation planning and policy.

Limitations

This project involved integration of multiple components grounded in a variety of distinct fields, including CAV technology, human factors, transportation planning, roadway design—both existing standards and emerging best practices—and computer-aided visualization. It also employed a variety of research methods—some of which the research team was forced to alter on-the-fly in response to the pandemic and its rippling ramifications across all aspects of society. Thus, the findings from this research are not presented—nor were they initially intended—as a definitive analysis of the impacts of CAVs on non-motorized road user safety or mobility. Rather, this work outlines the current thinking on ways in which transportation agencies are contemplating how CAVs will affect their work, their transportation landscapes, and their constituents. It also attempts to provide an example—using protected intersection principles—of how agencies can proactively adapt urban intersections to ensure the safety and mobility of all road users, from pedestrians to human-driven cars to fully-self-driving CAVs.

Our efforts to evaluate the impacts of the proposed intersection changes on pedestrians fell short of our expectations, however. Pre-pandemic best practices for understanding users' perceptions and attitudes about transportation facilities—*in situ* intercept surveys—no longer appear to be effective, as reflected in our very low survey response rates. Identification and development of new survey methods appropriate for a post-pandemic society was beyond both the scope and timeframe of this study; we are hopeful that our efforts—including the documentation of the challenges that arose during our survey—inform development of new best practices.

The options available to aid in visualization of proposed changes to the built environment have ballooned during the study period, thanks in part to the widespread introduction of consumer-grade generative AI. While we did not identify any off-the-shelf tools for intersection design that matched the flexibility of SketchUp as of this writing, we believe such tools are not far off. We expect that with these tools, the painstaking process of creating realistic 3D images and videos of proposed design changes employed in this project will be obsolete in the near future—a prospect we look forward to with cautious optimism.

Finally, we note that CAV technology, investor confidence in CAV companies, elected officials' appetite for regulating the CAV industry, and consumer attitudes toward using or purchasing CAVs are all fluctuating wildly. Our research gathered a snapshot of the perceptions among transportation professionals of the potential impacts—positive, negative, and uncertain—on their communities during the 2020-2022 time frame. This period may go down in history as one of the most tumultuous of modern times, and the transportation profession's collective knowledge and concerns about CAVs may well be different to what is reported here in the coming years.

Given the limitations of the survey, the enormous potential for advancement in visualization technology, and the huge uncertainties over CAV technology, regulation, and marketability, we strongly encourage on-going support for more research—including better post-pandemic research methods—in this arena by transportation agencies across the country.

Recommendations

Understanding CAV-readiness

Discussions about CAVs abound—among the general public and in professional settings. The debate is bedeviled by its very ubiquity, not to mention the lack of clear specific guidance for governments, transportation agencies, and the traveling public. That is, although we identified some cities leading the way on CAV-readiness, it cannot be—or hasn't yet been—reduced to a set of principles or features.

The CAV-readiness discussion necessarily must touch on technology (vehicles, infrastructure, communications), legislation (at all levels), policies and programs, associated concerns like insurance and marketing, and cultural shifts like travel behavior across modes and expectations and attitudes toward CAVs on our streets and roads. The parties to this discussion likewise should be broad and diverse—not only local and state government and transportation officials and police and emergency services, but the public at large, as specific populations who may have particular interest in and concern about CAVs (commercial sector, advocates for low-mobility populations, public health officials, and more).

Transportation professionals often rely on professional networks and associations for guidance, while the public may get their information from a broad—and not always reliable—collection of sources. An authoritative source of information and a neutral site for discussion would benefit all involved in the debate.

CAV-ready multimodal intersections

Future intersections should be multimodal—to accommodate CAVs but also protect and prioritize non-motorized travelers. With the need to adapt for CAVs by altering infrastructure and the potential for CAVs to change how road space is used, we have an opportunity to correct longstanding imbalances and inequities in safety and freedom of movement for all people by redesigning infrastructure to support all modes. Not doing the work now to understand how to capitalize on this opportunity—or worse, not taking the opportunity at all—carries the very real danger that knee-jerk reactions to rapid technological change will lock out non-motorized and/or unconnected travelers out of the system … or at least further compromise their safety and mobility.

Interest in multi-modal pedestrian-safe intersections is high, as part of the general movement for complete streets and compact, walkable urban environments. That interest should be activated and incorporated into planning for CAVs, so that the stated priorities of these planning efforts are not only efficiency and CAV accommodation, but also for safe, comfortable, appealing, lively streetscapes that bring people together and deliver them to their desired destinations and activities via the travel modes that work best for them.

Safety and mobility for people not in vehicles

The approaching CAV transition, and the shift to electric and—often—shared—vehicles expected to accompany it, offers an opportunity to prioritize at the same time non-motorized travel, which can address our many interlocking problems: safety, energy and environment, compact urban form for more sociable and equitable and appealing communities. If CAVs can be both accommodated and a force for improved conditions for all road users, then we must be prepared to create the conditions to ensure that is the future we have. If CAVs can reduce the number and severity of crashes, meet first/last mile needs of people with mobility limitations, and foster enhanced efficiency in transportation systems, then, again, we must be prepared to ensure the necessary supports are in place to capitalize on these benefits. But, as voiced by so many of the professionals with whom we spoke, the priority must be pedestrians, cyclists, and others who are present in the roadway environment outside of motor vehicles. CAVs present an opportunity to realize this priority, but only with intentional, proactive changes to the physical design of transportation infrastructure, including and perhaps starting with intersections.

Understanding impacts on pedestrians, cyclists, and other non-motorized road users

In recognition of NCDOT's interest and leadership in public engagement, this research attempted to develop and test a novel approach to gauging the impacts of changes to transportation infrastructure on its users. In the process, we learned that pre-pandemic best practices for understanding user perceptions and attitudes—*in situ* intercept surveys—are ill-suited for a post-pandemic society. We strongly encourage transportation agencies to support development and evaluation of new methods for public engagement that simultaneously take advantage of technological advances while increasing opportunities for meaningful participation for underrepresented and lower-resourced individuals—the very populations who stand to be affected the most by massive changes to our transportation systems.

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Appendices

Appendix A. City selection, vetting (ASU Planning studio)

Appendix A: Scoring Rubric for CAV Innovator Cities

Multimodal Transportation Plan

3	**2**	**1**
Multimodal transportation plan already in place	Current development or future development of plan	Has no multimodal transportation plan in place and/or no record of developing one

Future CAV Plans

3	**2**	**1**
Local Plans in place	State plans, or informal ideas within the local area	No current CAV speculation or planning involved

City CAV Policy Presence

3	**2**	**1**
Formal legislature currently enacted, being reviewed, or drafted on CAV presence and accompanying policy	No formal legislature in place, but presence of informal CAV policy and/or suggestions for policy	Has no current and/or future formal or informal legislature on CAV policy or inclusion

Presence of Pilot Programs

3	**2**	**1**
Yes	Not currently, but has been either discussed or in review for future implementation	No, and no plans for one

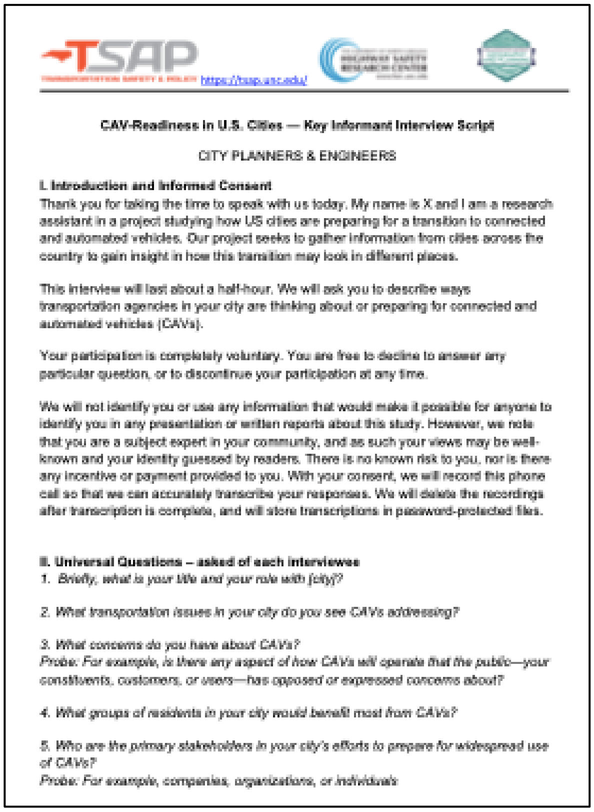
Partnership with CAV Companies

3	**2**	**1**
Yes	No, but has been either discussed or in review for future	No

Appendix B. Rubric for Instrument (ASU Planning studio)

Red Flag Zone (questions should not have the following components)	**Includes**	**Doesn't Include**
Yes/No - Type Question		
Leading Question		
Multiple-Part Questions		
Typical Standards	**Includes**	**Doesn't Include**
Does this question probe description rather than a reflection?		
Is this question relevant for the interviewee in question?		
Does this question progress the interview?		
Does the question include a potential probe?		
Specificity (Choose One)	**Includes**	**Doesn't Include**
Very Specific		
Somewhat Vague		
Vague		
What the Question Addresses (Choose One)	**Includes**	**Doesn't Include**
Knowledge		
Opinion		
Values		
Experience		
Behavior		
Background		
Demographic		
Category of Question (Choose One)	**Includes**	**Doesn't Include**
Hypothetical		
Ideal Position		
Devil's Advocate		
Interpretive Question		

Appendix C. Interview instrument (ASU Planning studio)



https://tsap.unc.edu/

CAV-Readiness in U.S. Cities — Key Informant Interview Script

CITY PLANNERS & ENGINEERS

I. Introduction and Informed Consent

Thank you for taking the time to speak with us today. My name is X and I am a research assistant in a project studying how US cities are preparing for a transition to connected and automated vehicles. Our project seeks to gather information from cities across the country to gain insight in how this transition may look in different places.

This interview will last about a half-hour. We will ask you to describe ways transportation agencies in your city are thinking about or preparing for connected and automated vehicles (CAVs).

Your participation is completely voluntary. You are free to decline to answer any particular question, or to discontinue your participation at any time.

We will not identify you or use any information that would make it possible for anyone to identify you in any presentation or written reports about this study. However, we note that you are a subject expert in your community, and as such your views may be well-known and your identity guessed by readers. There is no known risk to you, nor is there any incentive or payment provided to you. With your consent, we will record this phone call so that we can accurately transcribe your responses. We will delete the recordings after transcription is complete, and will store transcriptions in password-protected files.

II. Universal Questions – asked of each interviewee

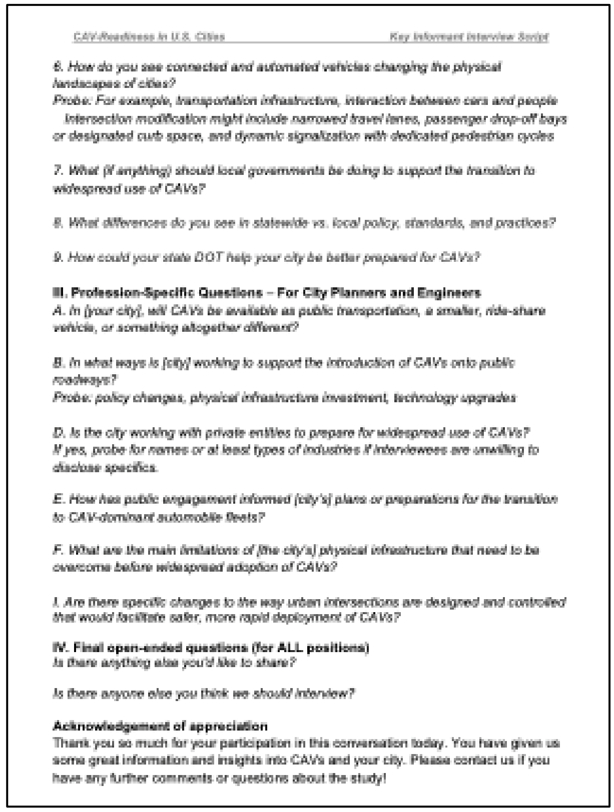
1. *Briefly, what is your title and your role with [city]?*

2. What transportation issues in your city do you see CAVs addressing?

3. What concerns do you have about CAVs?
Probe: For example, is there any aspect of how CAVs will operate that the public—your constituents, customers, or users—has opposed or expressed concerns about?

4. What groups of residents in your city would benefit most from CAVs?

5. Who are the primary stakeholders in your city's efforts to prepare for widespread use of CAVs?
Probe: For example, companies, organizations, or individuals



6. How do you see connected and automated vehicles changing the physical landscapes of cities?
Probe: For example, transportation infrastructure, interaction between cars and people
Intersection modification might include narrowed travel lanes, passenger drop-off bays or designated curb space, and dynamic signalization with dedicated pedestrian cycles

7. What (if anything) should local governments be doing to support the transition to widespread use of CAVs?

8. What differences do you see in statewide vs. local policy, standards, and practices?

9. How could your state DOT help your city be better prepared for CAVs?

III. Profession-Specific Questions – For City Planners and Engineers

A. In [your city], will CAVs be available as public transportation, a smaller, ride-share vehicle, or something altogether different?

B. In what ways is [city] working to support the introduction of CAVs onto public roadways?
Probe: policy changes, physical infrastructure investment, technology upgrades

D. Is the city working with private entities to prepare for widespread use of CAVs?
If yes, probe for names or at least types of industries if interviewees are unwilling to disclose specifics.

E. How has public engagement informed [city's] plans or preparations for the transition to CAV-dominant automobile fleets?

F. What are the main limitations of [the city's] physical infrastructure that need to be overcome before widespread adoption of CAVs?

I. Are there specific changes to the way urban intersections are designed and controlled that would facilitate safer, more rapid deployment of CAVs?

IV. Final open-ended questions (for ALL positions)

Is there anything else you'd like to share?

Is there anyone else you think we should interview?

Acknowledgement of appreciation

Thank you so much for your participation in this conversation today. You have given us some great information and insights into CAVs and your city. Please contact us if you have any further comments or questions about the study!

Appendix D. example survey, web format (Greensboro, Tate St and W. Gate City Blvd)

Re-imagining Intersections for a Multimodal Future

This survey is part of a study on how people interact with roads, intersections, and motor vehicles in North Carolina. For more information about this study, including how we will use your survey responses, please contact shaycombslab@gmail.com.

The survey will ask you to share your experiences navigating through a particular intersection. Your participation in this survey is voluntary and anonymous. The survey does not ask for personal information. You are under no obligation to complete this survey.

We estimate the survey will take 5 to 10 minutes. We are grateful for your time and your thoughts.

When you are ready to proceed, please tap or click the blue button below.

→

This survey focuses on the intersection of **Tate St** and **W. Gate City Blvd** in Greensboro, NC, shown below.

Have you traveled through this intersection in the past year?

- Yes (4)
- No (5)
- Not sure (6)

Skip To: End of Survey If Have you traveled through this intersection in the past year? != Yes

Display This Question:
If Have you traveled through this intersection in the past year? = Yes

How do you usually travel through this intersection?
Please check all that apply

- Bicycling (includes e-bikes and trikes) (1)
- Walking, jogging, or running (2)
- On a stand-up scooter (includes electric) (3)
- By wheelchair, mobility scooter, or other assistive device (4)
- By motorcycle (5)
- By bus (6)
- In a car or truck (includes taxis/shared ride) (7)
- Other (8)

The next several questions focus on traveling through this intersection as a pedestrian. For the purposes of this survey, "pedestrian" includes walking, running, or using a wheelchair or other assistive mobility device.

As a pedestrian, how often do you travel through this intersection?

- Never (1)
- Less than once per week (2)
- 1-3 times per week (3)
- More than 4 times per week (4)

Display This Question:
If As a pedestrian, how often do you travel through this intersection? = Never

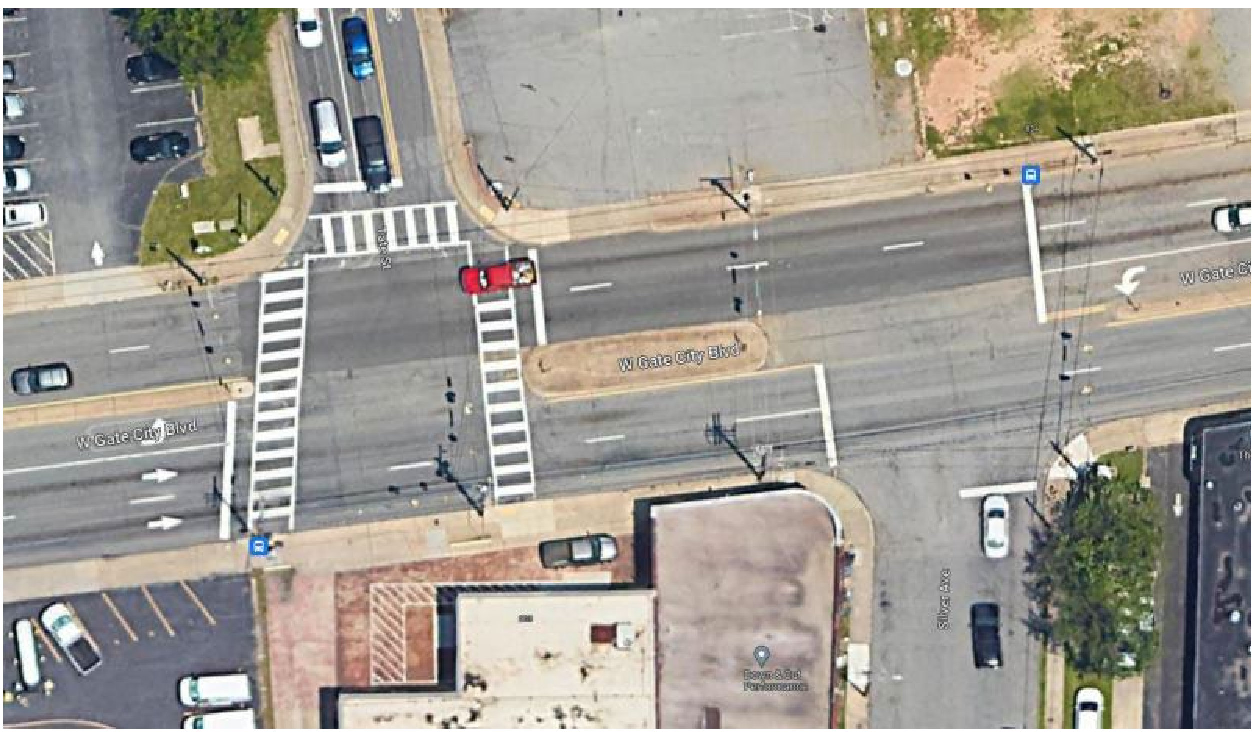
Why do you not travel through this intersection as a pedestrian?

- ☐ It's too far to walk to (1)
- ☐ It's not safe to walk here (2)
- ☐ It's not convenient to walk here (3)
- ☐ It's not comfortable to walk here (4)
- ☐ Other (5) ____

Display This Question:
If As a pedestrian, how often do you travel through this intersection? != Never

Think about your most recent journey through this intersection as a pedestrian. Please tap or click the screen to drop points along the route you followed.

Please note the interface will allow you to record up to ten points.



Display This Question:
If As a pedestrian, how often do you travel through this intersection? != Never

How safe did you feel crossing this intersection as a pedestrian?
Please drag the slider to indicate how safe you felt

	Very unsafe (like my life was in danger)	Very safe (I'd feel safe here with a small child)
()		

Display This Question:
If As a pedestrian, how often do you travel through this intersection? != Never

Please share any thoughts you have on improving this intersection for pedestrians

____
____
____
____
____

Display This Question:
If As a pedestrian, how often do you travel through this intersection? = Never

How safe would you feel crossing this intersection as a pedestrian?
Please drag the slider to indicate how safe you felt

Very unsafe (like my life was in danger) — Very safe (I'd feel safe here with a small child)

Display This Question:
If As a pedestrian, how often do you travel through this intersection? = Never

Please share any thoughts you have on improving this intersection for pedestrians

____
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At some point in the future we will likely share our roads with self-driving cars. These are also known as Connected and Automated Vehicles, or CAVs.

Would the presence of CAVs change how you feel about using this intersection as a pedestrian?

CAVs at this intersection would make me feel...

- ◯ Less safe (1)
- ◯ More safe (2)
- ◯ Neither more nor less safe (3)
- ◯ Not sure (4)

Some experts believe that for CAVs to operate safely and efficiently in cities, intersections will need to be redesigned. The images on the following screens show a hypothetical redesign of this intersection that would accommodate CAVs.

Please click the blue arrow at the bottom right of the screen to see the images.

→

This image shows Gate City Blvd from above, facing south from Tate St. The strips along the sides of the road and crossing the intersections in green are bicycle paths. The black and white striped areas are raised pedestrian crosswalks.

This image shows the intersection of Gate City Blvd and Tate St from above, facing southeast. Dedicated areas for bicyclists and pedestrians are protected from motor vehicle traffic with raised concrete curbs.

This image shows some of the detail at the intersection of Tate and Gate City Blvd from above, facing northeast.

How safe would you feel crossing this redesigned intersection as a pedestrian?
You may go back to look at the images again if you need

Please drag the slider to indicate how safe you felt

Very unsafe (like my life was in danger)	Very safe (I'd feel safe here with a small child)

Would the presence of CAVs change how you feel about using this redesigned intersection as a pedestrian?

CAVs at this intersection would make me feel...

- ◯ Less safe (1)
- ◯ More safe (2)
- ◯ Neither more nor less safe (3)
- ◯ Not sure (4)

Please feel free to share any comments or insights you have about sharing the street with CAVs

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Aside from this intersection, do you face any difficulties getting around in Greensboro as a pedestrian?

- ◯ Yes (1)
- ◯ No (2)
- ◯ Prefer not to answer (3)
- ◯ Not applicable (4)

Please feel free to explain any challenges you face getting around in Greensboro as a pedestrian.

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____
____

How old are you, in years?

- ◯ 19 or younger (1)
- ◯ 20 - 29 (2)
- ◯ 30 - 39 (3)
- ◯ 40 - 49 (4)
- ◯ 50 - 59 (5)
- ◯ 60 - 69 (6)
- ◯ 70 or older (7)

With what gender to you identify?

- ◯ Male (1)
- ◯ Female (2)
- ◯ Non-binary / third gender (3)
- ◯ Prefer not to say (4)
- ◯ My choice is not listed (5)

We thank you for your time spent taking this survey.
Your response has been recorded.

Appendix E. Example survey recruitment materials (Greensboro, Tate St and W. Gate City Blvd)

Figure 6. Example clipboard sign

Intersections for a Multimodal Future
Tate St and Gate City Blvd
Greensboro Walking Study

https://go.unc.edu/tate

Figure 7. Example survey information card, front

This survey is part of a study on how people interact with roads, intersections, and motor vehicles in North Carolina. For more information about this study, including how we will use your survey responses, please contact shaycombslab@gmail.com.

The survey will ask you to share your experiences navigating through a particular intersection. We estimate the survey will take 5 to 10 minutes. We are grateful for your time and your thoughts.

Appalachian STATE UNIVERSITY

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Figure 8. Example survey information card, back