How Technology can affect the Demand for Bicycle Transportation: The State of Technology and Projected Applications of Connected Bicycles

[1]John MacArthur (corresponding author) – *Email: macarthur@pdx.edu*
[1]Michael Harpool – *Email: mharpool92@gmail.com*

[1]Transportation Research and Education Center (TREC)
Portland State University
PO Box 751
Portland, OR 97207-0751
Phone: 503-725-8545; Fax: 503-725-2880

Submitted for presentation at the 98th Annual Meeting of the Transportation Research Board

Date submitted: 8/1/2018

Number of Words: 7,167
Number of Figures and Tables: 2 figures, 1 table (1 x 250) =250
Total Number of Words: 7,417

ABSTRACT

The term "connected vehicle (CV)" refers to vehicles equipped with devices which enable wireless communication between internal and external entities, supporting vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) communications. The widespread deployment of CVs will address a range transportation challenges related to safety, mobility, and sustainability. Recent research efforts on connected bicycles have focused on the uses and limitations of the state-of-the-art technologies, safety implications, the reliability of various communication modes, and consumer adoption. Existing research focuses on either technologies that utilize data received from sensors and the internet to govern devices attached to the bicycle (situational sensing) or two-way communication. While there has been some mention of how these technologies may encourage an increase in bicycling through enhanced safety, the research is sparse and there is a lack of discussion on how connected bicycles can address other barriers to bicycling. This paper will provide context into the societal needs of bicycling and the current strategies utilized to increase the bicycle mode share, a cohesive review of existing and prototyped connected bicycle technologies and discuss their potential to mitigate barriers to bicycling and better accommodate the needs and desires of diverse riders. We will then explore the limitations and benefits of one-way and two-way communications, the potential of bicycle-to-infrastructure technologies, and the future needs and expected pathways of connected bicycle technologies.

INTRODUCTION

Over the past two decades, federal, state, and local governments in United States have expressed a growing interest in supporting the needs and desires for individuals who chose to travel by bicycle. Concerns for public health and well-being, environmental degradation, and community livability have led to policies, programs, and infrastructural investments meant to enhance the opportunities and conditions for active transport. The primary goal of these efforts is to encourage a modal shift from single occupancy vehicles. However, numerous barriers continue to deter the use of bicycles over other modes and limit our cities capacity to realize the full potential of bicycle transportation.

The concern for safety reigns as one of the most significant deterrents, and in many neighborhoods in the U.S. these concerns are valid; the National Highway Safety Traffic Administration (NHSTA) reported that in 2015 there were 818 bicyclist fatalities and 45,000 injuries (1). Recent research suggests that bicycling rates would increase with improved separation and safety from automobile traffic (2; 3; 4; 5). Individuals are also deterred from bicycling by physical and environmental barriers (i.e. health, topography, and distance), unsatisfactory routes and navigation, bicycle security and maintenance concerns, the need to transport cargo and children, and other unmet needs. The city of Portland, already arguably one of the best large U.S. cities for bicycling, adopted in 2010 the Portland Bicycle Plan that aims to achieve a 25% mode share by 2030. Yet even with its cutting edge bike infrastructure, land use planning, and progressive programs, the U.S. Census reports that the 2011 bicycle commute mode share was 6.3%. Comparatively, the nationwide bike commute mode share is under one percent (7). These numbers indicate that there are social and physical barriers to bicycling that are not currently being addressed. Although these barriers have deterred the growth of cycling in the U.S., recent advancements in connected vehicle (CV) and bicycle technologies have the capacity to minimize these barriers and increase cycling.

The concept of CVs is not new; research efforts to gauge the reliability and practicality of CV technologies date back to the 1990s. The term “connected vehicle” refers to vehicles equipped with devices which enable wireless communication between internal and external entities, supporting vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) communications (8). CV technologies will support and enhance the benefits currently provided by vehicle-mounted detection systems. Recent advancements in sensor technology have enabled manufacturers, such as Jaguar Land Rover and Volvo to develop systems which can detect bicyclists, pedestrians, and other vehicles to help prevent crashes. The widespread deployment of CVs will address a myriad transportation challenges related to safety, mobility, and sustainability.

Since the early 2010s, CV application prototyping and assessment has been central to the U.S. Department of Transportation’s CV research and development activities (9). These efforts have led to the development of more than three dozen CV applications (Figure 1). These applications are essentially capabilities of CV technologies through V2V, V2I, and V2X communications. As shown in Figure 1, very few of these applications focus on pedestrians, and none of the applications make explicit mention of bicyclists; however many of the safety and mobility CV applications could benefit bicyclists.

From the outset, dedicated short range communication (DSRC) devices have been the favored technology to satisfy this role and are still considered the technology standard; however, cellular companies and associated 5G supporters have begun to push against any mandate, suggesting a market driven solution. These advocates claim that by the time DSRC is able to make any significant difference in safety, 5G cellular networks will be able to provide all of the same benefits and more (10; 11). In terms of the safety benefits of DSRCs, the NHSTA estimates that CV technologies have the potential to reduce up to 80 percent of crashes where drivers are not impaired (12).

Figure 1 U.S. DOT Connected Vehicle Applications

The notion of connected bicycles emerged in the early 2010s through two distinct yet interconnected conceptualizations. The first, focuses on one-way communication using sensors and modules which collect and transmit data directly to the bicyclist through the internet and other integrated devices. The technology that captures this information can be built-in (smart bike/e-bike) or brought-in (handlebars, helmets, bicycle computers, locks, etc.), and they tend to rely on integration with smartphone technology (13). The use of smartphones by bicyclists was spurred by the rise of wayfinding apps and sport tracking apps such as Strava; these apps continue to be a critical component of many connected bicycle technologies. The second is conceived as the integration of bicycles into the V2X communication environment. This concept relies on direct two-way communications between bicycles and vehicles (B2V) and infrastructure (B2I). Technologies for both concepts continue to be explored today with a common goal of enhancing the experiences and safety of the bicyclist (14; 15; 16).

Recent research efforts on connected bicycles have focused on the uses and limitations of the state-of-the-art technologies (13; 14), safety implications (17; 15), the reliability of various communication modes (18; 19), and consumer adoption (14; 15). While there has been some mention of how these technologies may encourage an increase in bicycling through enhanced safety, the research is sparse and there is an absence of discussion on how connected bicycles can address other barriers to bicycling. Furthermore, existing research seems to focus on either technologies which utilize data received from sensors and the internet to govern devices attached to the bicycle (situational sensing) or two-way communication. We believe that it is important to consider the two side-by-side to assess the existing conditions and future trends of the state of technology. This paper will provide context into the societal needs of bicycling and the current strategies utilized to increase the bicycle mode share; a cohesive review of existing and prototyped connected bicycle technologies; and discussion of their potential to mitigate barriers to bicycling and better accommodate the needs and desires of diverse riders. Finally, we will explore the limitations and benefits of one-way and two-way communication, the potential of bicycle-to-infrastructure (B2I) technologies, and the future needs and expected pathways of connected bicycle technologies.

Context and Background: Why is Bicycling Important?

In recent years, traffic safety for non-motorized users has become a significant public health issue and prioritized concern in U.S. cities. In 2015, there were 6,194 pedestrian (87%) and bicyclist (13%) fatalities and 115,000 injuries (61% and 39%, respectively) in the U.S. alone (1; 20). A study by the Federal Highway Administration (FHWA) found that over 18% of vehicle-bicycle collisions resulted in serious and fatal injuries to the bicyclist (21). In this study, the FHWA separated all collisions into three categories, parallel-path events (36%), crossing-path events (57%), and specific circumstances (7%). Of the parallel-path events, the most common crashes types included motorist turn/merge into bicyclist's path (12.2%), motorists overtaking the bicyclist (8.6%), and bicyclist turn/merge into motorist's path. For crossing-path events, the most common crash types were motorist failed to yield to bicyclist (21.7%), bicyclist failed to yield at an intersection (16.8%), and bicyclist failed to yield midblock (11.8%). These six crash types accounted for the vast majority of all vehicle-bicyclist collisions (21).

These crash statistics are indicative of the social need to enhance the safety margins for bicyclists. Increased efforts to improve the infrastructural conditions for bicyclist and pedestrians and provide supportive educational programs and traffic regulations have shown to have a positive effect on safety for non-motorized users (22). Encouraging more individuals to travel by bicycle could generate safer environments, which could ultimately attract more users and create safety in numbers.

Physical inactivity can increase an individual's chances of obesity, cardiovascular disease, diabetes, high blood pressure, depression, and other chronic diseases; it is estimated that inactive lifestyles are responsible for 200,000 deaths per year in the U.S., and more than 70% of U.S. citizens do not meet recommendations for physical activity (23). Sallis et al. (23) claim that active transportation has the capacity to contribute significantly to overall levels of physical activity and that even small increases in physical activity can improve public health. In a review of the literature, Pucher and Buehler (22) reveal that active transportation is directly related to improved health in older adults, decreased mortality rates, and improved resting blood pressure. Their findings suggest that bicycling and walking to work can be one of the most practical and effective ways to meet recommended physical activity levels.

Since 1980, the number of vehicle miles traveled (VMT) each year has increased dramatically and has grown three times faster than the U.S. population (24). Rapid growth in VMT has led to alarming rates of greenhouse gas emissions (GHG), especially carbon dioxide (CO2); the transportation sector is the largest source of GHG emissions, accounting for 28.5% of the national total (25). Studies have shown that even with technological improvements for fuel efficiency, CO2 emissions will continue to rise without a significant decrease in VMT (24). In this light, bicycles and other alternatives to gas powered vehicles have become an increasingly attractive solution. Increasing the proportion of people that travel by bicycle can dramatically decrease VMT and the levels of harmful pollutants emitted into the environment.

Encouraging Active Travel

A growing body of research shows that an increase in active transport can be achieved through infrastructural improvements, enhanced access to facilities, supportive policies, advocacy and outreach and promotion programs (26; 27; 28; 29). Correspondingly, a growth in the public presence of bicycling can encourage even higher rates of bicycling. Technology is another component with the capacity to encourage more bicycling, yet it is often overlooked by active transportation professionals, city planners and advocacy groups.

We reviewed 25 regional and city bicycle plans and eight vision zero plans. In general, the plans make little to no reference to connected technology as a component of city bicycle planning. Twenty of the plans and 8 of the vision zero plans do discuss the importance of signalized intersections, signal prioritization and actuated bicycle detection devices. Only three plans mention e-bikes as a device that need to be considered for use and in future planning. This cursory analysis shows that bicycling planning is not keeping pace with technology advancements. One possible reason for the lack of technology being included in these plans is that only five plans where developed after 2015.

As with other modes, the propensity to travel by bicycle is dependent on the cohesiveness, functionality, safety, and accessibility of the transportation network. Investment in active transportation infrastructure has increased dramatically in recent years, and there is considerable evidence that these investments can lead to significant increases in active travel. Numerous studies demonstrate a positive correlation between the quantity of bicycle infrastructure within cities and rates of bicycle transportation (30; 31; 32). In North America, the real and perceived risk imposed by motor vehicles is the primary reason individuals do not ride more frequently (6); these studies show that providing designated spaces for bicyclists (i.e. bike lanes and separated paths) can reduce that risk and increase the attractiveness of bicycling for demographics other than those who are comfortable riding in traffic. Scholars have also studied how different policies and programs may impact levels of active transportation (33; 34; 35; 36). Aside from promotional programs, it is essential for municipalities to provide support for bicycling through local and regional plans. Aytur et al. (37) found that counties which included non-automobile transportation improvements and a comprehensive set of policies to guide development in their land use plans had higher levels of transportation- and leisure-oriented physical activity.

The strategies mentioned above seek to address the barriers to bicycling as well as the fundamental mobility needs of bicyclists. Advancements in bicycle technology could contribute significantly to this challenge; yet, technology has surprisingly received little attention from scholars and practitioners in this field. The studies that do exist have looked at the role of developments in bicycle equipment and electric assist. Lovejoy and Handy (38) argue that developments in bicycle components (e.g. frame, brakes, and electric assist) and gear (e.g. lights, helmets, and trailers) can help improve the bicycling experience (e.g. safety, reliability, and the need to carry cargo); this is critical because individuals with various transportation options will be more apt to choose bicycling if the experience is competitive with other modes. In a study of e-bike use in North America, MacArthur et al. (39) found that electric assist technologies can encourage greater rates of bicycling. Respondents in this study reported that e-bikes had encouraged them to ride more often and ride for longer trips not necessarily feasible on a standard bicycle. Furthermore, e-bikes attracted individuals who previously did not ride a bicycle or had health conditions which limited their ability to ride a standard bicycle. Similarly, a study in Portland Oregon found that e-bikes facilitate travel to more distant locations, more frequent riding, and participation amongst a wider range of users by reducing the impact of certain barriers such as hills and heavy perspiration (40).

These studies demonstrate how developments made by bicycle and bicycle accessory manufacturers can address some of the unmet needs and desires of utilitarian bicyclists; however, a similar study has not yet been conducted on the recent advancements in connected bicycle and V2X technologies. It is our contention that the proper promotion and integration of these technologies could significantly increase the bicycle mode share and foster safe and livable communities. In the following section we will discuss the applications of these technologies and the specific barriers and needs they can address.

Connected Bicycles

Although the U.S. DOT CV applications mentioned in Figure 1 focus primarily on V2V and V2I communication, they can be useful for thinking about how new technologies could improve conditions for non-motorized road users in the future. After reviewing each of the applications we identified those which could potentially benefit bicyclists. These applications are listed in Table 1 along with a list of additional applications not considered by the U.S. DOT. These were developed through an extensive scan of connected bicycle technologies to acknowledge connected bicycle applications currently available to bicyclists. Table 1 also cites the specific barriers addressed by each application, whether the application could be supported by two-way communication modes, and whether they rely on sensor information. Below we will explore the relevant applications of situational sensing technologies and of two-way communications, focusing on how they can facilitate a better and safer bicycling experience.

Situational Sensing

Situational sensing encompasses a myriad of technologies which have been developed to enhance the bicycling experience. Many of these technologies are equipped with sensors and modules (e.g. accelerometers, gyroscopes, GPS chips, light and motion sensors, etc.) which collect data that can be shared to the internet and with the bicyclist through a smartphone and/or other integrated devices which can make use of the information. The type of data gathered by these devices can be categorized into four groups: *trip information* (e.g. route, speed and distance), *bicyclist information* (e.g. heart rate, blood pressure, and endurance), *bicycle status information* (e.g. tire pressure and battery life), and *environmental information* (e.g. pot holes, weather, topography, and traffic). However, not all of the situational sensing devices utilize sensor technology. Some devices connect to compatible smartphones and utilize data from the internet (e.g. navigation devices) and others communicate directly with compatible local devices for less complex tasks (e.g. hands-free calling and turn signal activation). Bicycle manufacturers and technology companies have developed both brought-in (smart locks, bicycle computers, mounted taillights and headlights, etc.) and built-in (instrumented bicycles and e-bikes) situational sensing products. Advancements in connected wearables, especially helmets also play an important role in the connected bicycle system, because they provide a platform to transmit audible and visual alerts to the bicyclists as well as surrounding road users. Although many of these devices, transmit, and make use of real-time information, they are not in direct and continuous communication with surrounding entities or other road users. Figure 2 depicts a situational sensing environment.

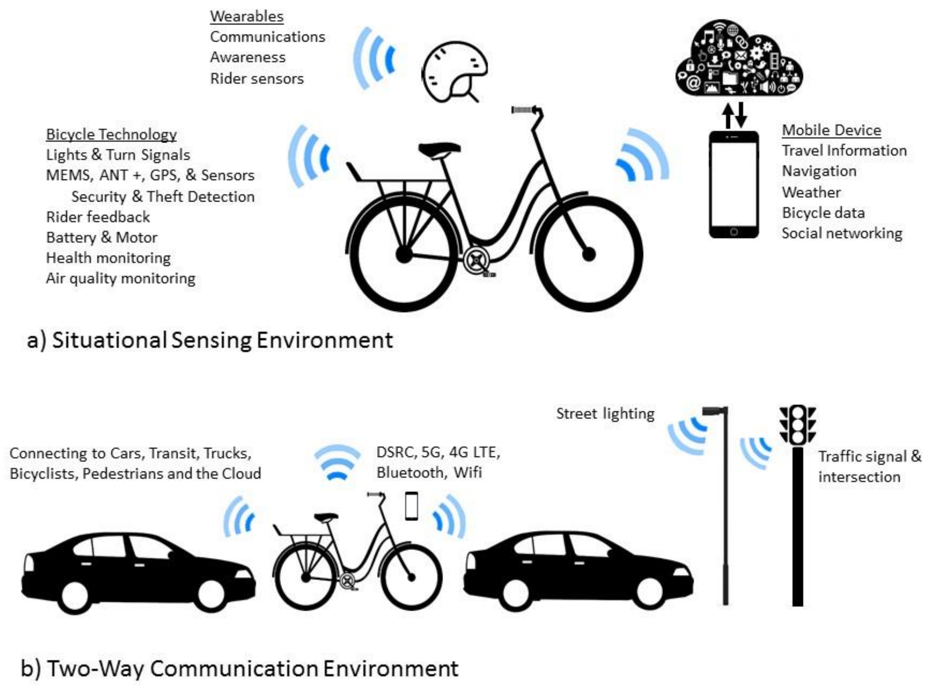

Figure 2 Connected Applications

Safety Barriers: Several connected bicycle technologies can detect and alert bicyclists of approaching vehicles. These devices most commonly come in the form of a mounted taillight. The Garmin Varia accomplishes the task by using an integrated radar which reports the approximate distance of approaching vehicles to a handlebar mounted display. The Hexagon taillight contains a HD camera, which allows the bicyclist to stream live videos through their smartphone. See.Sense ICON utilizes sensor technology to identify risky situations, such as an encroaching vehicle, and reacts by flashing brighter and faster – alerting both the bicyclist and oncoming traffic. The COBI connected bicycle system also delivers a taillight with collision avoidance technology and turn signals, and Ford's MoDe e-bike proposed vibrating handlebars that would notify the bicyclist of overtaking vehicles (41). A study by the League of American Bicyclists (7) found that 40% of fatalities with reported collision types were rear end collisions. These devices could greatly enhance the bicyclist's awareness allowing them to adjust their position or behavior in a timely manner to prevent a collision. They also increase the visibility of the bicyclists, which is especially important at night when safety margins are often insufficient; bicyclist fatalities most commonly occur between the hours of 6:00 and 9:00 p.m. in low light conditions (1).

Table 1 Barriers to Cycling and Connected Applications

Barriers		Applications		Communication			Sensors	
Barrier Classification	**Barrier Specification**	**Applications**	**U.S. DOT Applications**	**DSRC**	**Cellular B2V**	**Cellular B2I**	**Vehicle Sensor**	**Bicycle Sensor**
Safety Barriers	Bicycle-Vehicle Collisions	Approaching Vehicle Detection and Warning; Reactive Bicycle Lighting and Turn Signals; Collision Detection and Emergency Contact	Red Light Violation Warning; Ped in Signalized Crosswalk; Emergency Electronic Brake Lights; Forward Collision Warning; Blind Spot/Lane Change Warning; Vehicle Turning Right Warning; Intersection Movement Assist	Yes	Yes	Yes	Yes	Yes
	Mobile Phone Distractions	Turn-by-Turn Navigation; Hands-Free SMS and Calling		No	No	No	No	No
	Dangerous Routes and Intersections	Reactive Bicycle Lighting and Turn Signals; Social Networking	Forward Collision Warning; Advanced Traveler Information System	Yes	Yes	Yes	No	Yes
	Street/Path Lighting	Smart and Adaptive Lighting		Yes	No	Yes	No	Yes
	Bicyclist Visibility	Reactive Bicycle lights and Turn Signals		Yes	Yes	No	No	Yes
Physical Barriers	Physical Health	Electric Assist; Route Preference; Health Monitoring; Collision Detection & Emergency Contact		No	No	No	No	Yes
	Topography	Electric Assist; Route Preferences		No	No	No	No	Yes
	Distance	Electric Assist; Route Preferences		No	No	No	No	Yes
Navigation/ Mobility Barriers	Routing Options	Popular Routes; Route Preferences; Social Networking	Advanced Traveler Information System	No	No	No	No	No
	Route Obstructions	Pothole Detection; Social Networking	Forward Collision Warning; Advanced Traveler Information System	Yes	Yes	Yes	Yes	Yes
	Mixed-Traffic Intersections		Interaction Movement Assist; Intelligent Traffic Signal Systems	Yes	Yes	Yes	Yes	Yes
Additional Barriers	Bicycle Security	Lock, Alarm, & Track; Theft Detection		No	No	No	No	Yes
	Children/Cargo	Electric Assist; Route Preferences		No	No	No	No	Yes
	Bicycle Community	Performance Monitoring; Social Networking; Bicycle Sharing		No	No	No	No	Yes
	Mechanical Issues	Maintenance Status and Repair Prediction		No	No	No	No	Yes

Numerous connected bicycle technologies can detect a crash utilizing data collected from an onboard accelerometer. When devices like the Ellipse smart lock, Garmin Edge, The BikeSpike, or Cosmo detect that a crash has occurred they send a message to the bicyclist's smartphone asking whether or not they wish to have an alert with their location sent to their emergency contacts; if the bicyclist does not respond in a given amount of time the alert will be sent.

Turn-by-turn navigation is another popular safety application. This feature can help reduce the risks associated with mobile phone distractions. Numerous connected devices can link to compatible navigation apps on the bicyclist's smartphone through Bluetooth connection and provide alerts of upcoming turns through haptic (SmrtGrips), visual (Beeline and SmartHalo), and audio alerts (COBI and Sena X1). If the apps being utilized can effectively receive traffic updates and road condition information, the connected bicycle features can direct bicyclists away from potentially dangerous intersections and routes. Shoka Bell and SmrtGrips propose to use real-time traffic alerts and community-sourced information to assist bicyclists along the safest route while avoiding dangerous intersections. A few technologies, such as COBI and the Sena X1 helmet offer the ability to make and answer phone calls without removing ones' hands from the handlebars.

Physical Barriers: Many individuals face physical limitations which may deter them from bicycling, such as health conditions, living in a hilly area, and living far from where they work and play. Studies have found that electric bicycles (e-bikes) can be useful for mitigating the effect of these barriers (40; 42; 43). E-bikes provide a unique opportunity to enhance the development of connected bicycles, because they come equipped with a battery which can serve as a platform for integrating sensor technologies. Companies such as Stromer, Vanmoof, and VisioBike, have begun to take advantage of this opportunity. Each of these companies has developed an e-bike with integrated Bluetooth sensor technologies which transmit data to other connected devices within the bicycle (i.e. dashboard, lights, motor, etc.) and/or compatible smartphone apps. These features and the crash detection technologies discussed above can be especially important for individuals facing health barriers by providing additional awareness to help avoid an incident or pedal assistance.

Navigation/Mobility Barriers: While navigation apps have been widely available for bicyclists, they are an integral part of the connected bicycle infrastructure and could greatly benefit from some of the advantages of connected bicycles. Many of the technologies which are compatible with popular navigation and tracking apps like Strava and Garmin Edge or provide a navigation interface through their own app offer features such as fastest route, shortest route, most popular route, safest route, and even quietest route (COBI). The latter three features can be derived from information voluntarily published within the bicycling community (i.e. route data, pothole location, previous collisions, etc.) and data collected from onboard sensors and shared to the internet (ground surface condition, ambient noise, etc.). These features are essential to increasing the total number of trips taken by bicycle because not knowing how long a trip will take or the quickest and safest way to get to a destination can be a significant deterrent for choosing to travel by bicycle; the data collected and shared regarding specific urban and suburban routes via connected bicycles can help to reduce the impact of this barrier. Tracking and sharing performance data facilitates goal-oriented riding and friendly competition, and can encourage individuals to ride further, harder, and more frequently (44). Friendly competitions such as Portland, OR's Bike More Challenge are commonly used as a strategy to increase rates of bicycling. These devices also make it easier for individuals with varying health conditions to monitor important metrics which could permit the prevention of a health related incident while bicycling.

Additional Barriers: The fear of having a bicycle stolen can be a significant deterrent for certain types of trips and/or trips to certain destinations. It could also discourage an individual from purchasing a bicycle.

Brought-in and built-in connected bicycle technologies can significantly increase bicycle security. Bicycle mounted devices such as Shoka Bell, and B.Guard utilize motion sensors to detect theft, and when suspicious movement is detected, they activate an alarm and send an alert to the owner through a compatible app or SMS message. These and other devices are also equipped with GPS chips, allowing the owner to track their bicycle if the theft is not prevented.

Two-Way Communication

DSRCs, the proposed technology behind V2X communications, allow equipped road users to transmit data (speed, heading, position) at low latency up to 10 times per second. These messages can be received by other equipped entities (e.g. other road users and infrastructure) within an approximate range of 300 meters. All equipped entities are continuously transmitting and receiving data via two-way communication modes (see Figure 2). The messages are used to detect potential dangers imposed by traffic, terrain, or weather and provide the user with appropriate warnings. Currently, these devices are most widely considered for their potential to reduce the risks of vehicle-to-vehicle collisions and V2I communication; however, as mobile DSRCs have become available, researchers have begun to assess their potential to enhance safety for bicyclists and pedestrians (18; 17; 19). Field tests have revealed numerous challenges, such as size, GPS limitations and battery drain caused by the intensive task of continuously transmitting, receiving, and interpreting data. Researchers have also tested the potential of providing V2X communication through integrated mobile devices utilizing 5G cellular connectivity (45). Tome Software has partnered with Trek Bikes to develop a B2V communication system that relies on cellular connection (16).

The data generated through the process of two-way communication will help cities identify important traffic trends (e.g. collision hot spots, travel speeds, road user behavior, etc.) and support smart city initiatives. These data would contribute significantly to the information collected by existing technologies such as traffic monitoring sensors. NUMINA's streetlight mounted sensors are able to differentiate between all types of traffic, including bicyclists, pedestrians, and motorists, which enables the collection of important multimodal travel data (46).

<u>Safety Barriers</u>: It should be expected that successful implementation of B2V and B2I communication networks would provide bicyclists with many of the same safety benefits projected for CV operators. Bicyclists would be able to alert other road users of their presence and receive warnings regarding potential collisions, dangerous intersections, encroaching vehicles, and road hazards and conditions. The connection between bicyclists and other road users will provide the necessary road users with the appropriate alert, prompting them to take action to avoid a collision or dangerous situation. On the motor vehicle side of things, additional measures, such as automatic breaking will provide further support. It should be expected that such significant enhancements in actual and perceived safety could result in increased levels of bicycle travel (15).

B2I connection could permit communication between bicyclists and equipped street lights, traffic signals, road-side units, and surface infrastructure. B2I technologies could reduce the number of right hook accidents caused by motorists, support smart and adaptive lighting and signal prioritization applications, and provide bicyclists with red light violation warnings. Intelligent transportation infrastructure would be able to recognize dangerous driving behavior and notify nearby bicyclists so they can take the appropriate actions to avoid a potentially dangerous situation. Equipped street and path lights could recognize approaching bicycles and enhance visibility in low-light conditions, which could be especially vital to individuals residing in areas where crime may be a more significant barrier to bicycling.

<u>Navigation/Mobility Barriers</u>: Certain connected applications could also enhance the traveling experience for bicyclists. B2I communication would permit signal prioritization for cyclists; the ability of Intelligent Traffic Signal Systems to recognize and prioritize bicyclists could greatly reduce the number of stops and

starts required on a given trip. Currently, relevant research efforts are focused on V2I communication utilizing DSRC; however, technology companies have explored utilizing Bluetooth integrated infrastructure to communicate with nearby smartphones through an interface provided by a compatible app (47). Similarly, the Tampa Connected Vehicle Pilot introduced a smartphone app which allows pedestrians and bicyclists to request a “walk” signal at select intersections (48). Successful B2I communication could improve travel time and reduce physical effort required for a bicycle trip by reducing the frequency of stops.

Limitations and Benefits

When compared, each connected bicycle environment has a unique set of limitations and benefits. However, there are some limitations that they share, which are inherent in the mass distribution of data and reliance on various technological components (i.e. modules, sensors, connection modes). Cyber security and remote hacking are amongst the more significant challenges and fears associated with CV and bicycles; an international consumer survey found that 34% of vehicle owners currently do not trust either automakers or technology companies with their in-car data and privacy (49). With no full-proof way to protect DSRCs or other devices from being accessed remotely, attackers could manipulate data and share falsified information.

GPS capabilities have also proven to be a significant challenge for both cellular C-V2X and mobile DSRC communications; GPS coordinates can easily be distorted due to a blockage of signal by physical barriers such as tall buildings or trees (18; 50). This can adversely impact the functionality of situational sensing devices and two-way communication systems. With two-way communications the risks could be more substantial; inaccurate coordinates could generate false warnings in harmless situations or no warnings in potentially dangerous situations (51).

The primary benefit of situational sensing devices is that their utility is not entirely dependent on the number of users within the network. While in some cases the benefits would increase with more equipped users, the devices can function in the absence of other connected devices. On the other hand, two-way communication cannot be achieved if surrounding road users are not connected, and even with the passing of the federal DSRC mandate this could take decades to achieve. However, in the case where all road users are connected, the actual safety and mobility benefits will likely be much greater than those provided by devices which only alert the bicyclist or driver. Having collision prediction alerts sent to the vehicle could also permit the use of emergency braking services, which would enhance the safety margins for bicyclists. Only a few situational sensing devices make any attempt at communicating with surrounding road users, and the communication capabilities of those that do are limited. For example, the See.Sense Icon taillight reacts to its environment and flashes brighter and faster in dangerous situations, which requires the driver to acknowledge and understand the message behind the signal.

It is expected that B2V communication in congested urban areas will result in an overabundance of warning messages sent to drivers and bicyclists, regardless of whether there is imminent danger. Researchers claim that a high quantity of messages, spurious or real, will cause annoyance and lead to moderate to high non-usage rates and disregard for the warnings (15). Furthermore, these warnings could distract road users and lead to crashes; Tome attempts to address this issue by utilizing a system, which sends alerts to the driver rather than the bicyclist.

While improving safety and mobility measures tend to be the central focus of the CV dialog, it is important not to disregard the additional benefits provided by connected bicycle technologies. Innovations in situational sensing devices has enabled theft detection and GPS tracking, adaptive electric assist for e-bikes, simplified smartphone interaction, innovative use of social networks, and increased awareness of maintenance requirements. These applications do not necessarily pertain to B2V communication, yet they can significantly enhance the riding experience and make bicycling a more competitive transportation option. It is evident that there are numerous benefits tied to the advancement of these technologies, yet certain challenges and limitations, internal and external, may hinder their effectiveness.

Discussion: Existing Conditions and Expected Pathway

The question of whether bicycles simply detect vehicles and infrastructure (or vice versa) or there will be direct communication between them is fundamental to the future of a connected transportation network. Currently, the readily available technologies seem to support the former option; both automakers and bicycle manufacturers provide sensor technologies which permit the detection of other road users. For example, some new vehicles come equipped with blind spot detection and pedestrian and bicyclist detection technologies which alert the driver and can enable emergency braking services, and connected bicycle devices such as the Garmin Varia can detect and alert the bicyclist of encroaching vehicles. While very few vehicles are currently sold equipped with DSRCs, there is tremendous federal and private support for CV technology.

The U.S. DOT Connected Vehicle Pilot Program has initiated projects with New York City, Tampa, and Wyoming to support the deployment of CV technology (52). While the projects primarily focus on enabling V2V and V2I communication to support CV applications, both the NYC and Tampa projects include a vehicle-to-pedestrian (V2P) component. The V2P technologies provide equipped infrastructure with the abilities to warn vehicles of pedestrians and bicyclists within the crosswalk of an upcoming intersection, allow pedestrians and bicyclists to request a "walk" signal at select intersections (Tampa), and enhance intersection mobility for disabled and visually impaired pedestrians.

Although there is no direct communication between the pedestrian or bicyclist and the vehicle (i.e. pedestrians/bicyclists are detected by a roadside unit which alerts nearby vehicles), the technologies demonstrate the feasibility of connectivity for non-motorists utilizing mobile devices. Similar technology could be used to provide signal prioritization for bicyclists and direct B2V communications, yet this does not appear to be central to the current U.S. DOT CV mission but could lead to conceptual and technological advancements, which support and enable direct communication with vulnerable road users.

As sensor technologies continue to improve and prices decline, they will likely become more widely used and available. A high adoption rate of these devices could significantly enhance road safety and reduce collisions for bicyclists. It is our contention that the benefits of situational sensing devices will eventually be supported and enhanced by two-way communication. Two-way communications will not render situational sensing devices obsolete, because many of them support applications which are not supported by direct communication between other road users and infrastructure. However, they will enhance the safety benefits by enabling greater awareness of the surrounding environment and better address bicyclists' mobility needs by permitting signal prioritization and advanced traveler information systems.

Conclusions

As the societal benefits of active travel come to fruition in the U.S., cities seek to encourage bicycling by addressing the specific barriers and needs of the mode's diverse users. Advocates, academics, and practitioners often focus on the impacts of infrastructure, policies and programs, and access, yet technology tends to be ignored as a critical component of increasing bicycling rates. In this paper, we examined the existing and projected applications of connected bicycle technologies and explored the ways in which they could address some of the barriers to bicycling. Table 1 provided a list of these applications, some of which were pulled from the U.S. DOT's connected vehicle applications and the others were developed after reviewing the capabilities of existing connected bicycle technologies. The information in Table 1 links each barrier to the appropriate applications and considers the communication type and sensor technology, which provides a framework for future development and discussion around connected bicycles.

In conducting this research it has become evident that there is a lack of consideration of bicyclists in the U.S. DOT, state DOT, and local DOTs CV initiatives. The U.S. DOT has spent over five years developing more than three dozen CV applications, yet none of them directly acknowledge the presence of bicyclists on the road. As a result, there is limited mention of bicyclists in both the New York City and Tampa Connected Vehicle Pilot Programs. In these projects bicyclists take the same role as pedestrians in that their presence is recognized by pedestrian detection technologies and they can request a “walk” signal utilizing a smartphone app at select intersections. However, it is projected that many of the CV applications could benefit bicyclists in the same way they do motorists. We believe that bicycle manufacturing companies, bicycle advocates, and active transportation planners should be included in the connected vehicle conversations taking place at all scales of government. As connected technologies advance these groups have a unique opportunity to explore new concepts and encourage the integration of connected bicycles.

If bicycling is not considered a competitive transportation option within communities it is unlikely that the mode share will increase. Governments are often looked upon to address this challenge; however, private actors such as bicycle manufacturers and technology companies also play an integral role.

ACKNOWLEDGEMENTS
This project was funded by the National Institute for Transportation and Communities (NITC) under grant number (759).

The authors confirm sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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