Comparing safety-related riding behaviors on bicycles and electric bicycles.

Brian Casey Langford (Corresponding author)
Special Projects Coordinator
Center for Transportation Research
University of Tennessee-Knoxville
505 Deaderick St.
James K. Polk Building, Suite 900
Nashville, TN 37243-0344
Phone: (615)532-5824
Fax: (615)532-8451
E-mail: blangfo1@utk.edu

Jiaoli Chen
PhD Candidate
Department of Geography
304 Burchfiel Geography Building
University of Tennessee, Knoxville, USA 37996
Phone: 865-297-2910
Email: jchen42@vols.utk.edu

Christopher Cherry
Associate Professor
Department of Civil and Environmental Engineering
University of Tennessee-Knoxville
321 John D Tickle Building
Knoxville, TN 37996-2010
Phone: (865)974-7710
Fax: (865)974-2669
E-mail: cherry@utk.edu

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ABSTRACT

As electric bicycles (e-bikes) have emerged as a new transportation mode, their role in transportation systems and their impact on users have become important issues. The performance of e-bikes provides some benefits to users, compared to regular bicycles, such as a reduction in user effort required for similar trips, increased range, and increased speed to name a few. The performance characteristics of e-bikes could influence the behavior of riders and could influence on user safety. This work uses GPS data collected during user trips on both e-bikes and regular bicycles, which are part of an on-campus e-bike sharing system, to study user safety behavior between bicycle and e-bike modes. This report focuses on behaviors observed under four situations: 1) riding behaviors on directional roadway segments, 2) riding behaviors on shared use paths, 3) stopping behavior at stop-controlled intersections, and 4) stopping behaviors at signalized intersections. Behavior is studied in each situation and analyzed with regard to the desired, or safest, behavior. Results show some differences in behaviors between users of the two bicycle types but indicate that bicycle type has a small influence on safety behavior as compared to facility characteristics and other factors.
INTRODUCTION

In recent years, electric bicycles, or e-bikes, have emerged as a new, sustainable form of active transportation. While e-bikes are similar to regular bicycles in terms of function, they offer differences in terms of performance through the addition of an electric motor, which provides some level of assistance to the user during travel. Different e-bike models provide this assistance through different methods including pedal-based assistance, throttle-controlled assistance, or a combination of the two. The e-bikes considered in this study incorporate a pedal-based assist delivered when the user applies force through the pedals. Compared with regular bicycles, e-bikes could provide some benefits with regard to travel range and effort required by the user, promoting increased travel distance, easier acceleration from stops, and higher average speeds while overcoming challenging terrain and other obstacles. It is unclear how these benefits may affect user behavior, particularly related to safety.

The differences in performance between the two modes raise important questions about the safety of users on the two bicycle types. Following these concerns, much of the regulation on e-bikes, worldwide, is focused on safety concerns [1]. In the United States, while e-bikes are a relatively new mode of transportation, there are existing concerns for the safety of bicycle users. In New York, e-bikes are illegal because they are not considered bicycles due to the on-board motor and not motor vehicles as they are not registered and because the increased speed associated with e-bikes is considered riskier [2, 3]. The State of California requires helmets for users of e-bikes but not for users of regular bicycles; it also requires e-bike users to be 16 years old or older [4]. According to the Bureau of Transportation Statistics [5], 4,654 pedestrians and 698 cyclists were killed in traffic crashes in 2007. In the United States, cyclists are 12 times more likely to be killed in an accident than a driver of an automobile [6]. While an increase in modal share for non-motorized transportation generally results in fewer fatalities per user, an increase in the number of vulnerable road users could result in an overall increase in injuries and fatalities for users in that group.

Bicycle Safety

The impacts of bicycling on safety and health have been investigated by many studies, although comprehensive analysis of the combined impact of these parameters is not often considered. Leden et al. [7] developed a model to estimate safety risk for bicyclists based on speed data and expert evaluations of various components such as initial vehicle speed and risk of collision. The bicyclist intersection safety index developed by Carter et al. [8] also incorporated expert opinion of several situations through the form of safety ratings. That study also analyzed video footage of various intersections and modeled safety risk based on observed avoidance maneuvers, without which a crash would likely have occurred. A bicycle network analysis tool for comparing perceived safety for bicycles on various facilities was developed by Klobucar and Fricker [9]. One common thread amongst these models is the inclusion of user or expert perception about the safety of the facilities in question.
Other studies have investigated bicycle-related crashes at intersections. Wang et al. [10] modeled collision risk between bicycles and automobiles at signalized intersections, and Schepers et al. [11] modeled bicycle-automobile collisions at unsignalized intersections. These models highlight the role of intersection geometry and, at signalized intersections, the role of phasing on collision risk. Weinert et al. [12] studied e-bike use in Shijiazhuang, China, and found that, among other conclusions, e-bikes promote a perception of increased safety compared to regular bicycles at intersections.

The behavior of the cyclists themselves, for instance route choice, speed, and other behaviors, also has a large influence on safety. By relating route information of bicyclists to facility attributes in a geographic information system (GIS), Aultman-Hall et al. [13] studied the exposure of cyclists on roadways, on off-road paths, and on sidewalks, finding that the relative rates for falls or injuries was least on roadways, followed by off-road paths, and lastly by sidewalks. A study of bicycle users in Brazil found that, while most cyclists, over 95%, agree they should respect traffic rules, a significant number of them violate basic traffic safety laws such as running red lights or riding the wrong direction on the street [14]. That study found that violating traffic rules as well as riding seven days per week, as opposed to riding fewer days each week, increases the risk of an accident. An Australian study shows that most crashes involving adult cyclists occur in the roadway, primarily at intersections; however, for adolescents, most crashes involve a cyclist entering the roadway from a sidewalk and colliding with an automobile [15].

Educational efforts to curb dangerous or risky cycling behavior are not always successful. In one study, over 1,000 individuals in Brazil were invited to meetings, which included educational material covering bicycling safety in traffic, distribution of a safety kit, and bicycle maintenance as necessary. Many cyclists did not attend, and there was no observed effect from the meetings on either the number of accidents or near-accidents [16]. Furthermore, a study of adolescents, age 13 to 18, in the Netherlands shows that not only do they often violate traffic rules while cycling, many of them are aware that they are conducting risky cycling behavior [17].

The issue of safety is particularly important because of the vulnerability of users of active transportation. In China, for instance, although the total number of deaths resulting from traffic crashes and the number of regular bicycle related deaths have decreased, the number of casualties resulting from crashes involving e-bikes has risen. This is also true for non-fatal injury cases. As the number of injury cases involving regular bicycles has decreased, the number of injury cases for e-bikes has risen [18]. A possible explanation for this increase in e-bike injuries is the modal shift from regular bicycles to e-bikes.

**Introducing new technologies through e-bike sharing**

Along with the introduction of e-bikes as a new transportation mode, another recent innovation is bicycle sharing. Bikeshare systems have emerged around the world [19-21] with many systems installed in the United States in recent years as well [22-24]. As an evolution of bikesharing, the integration of e-bikes with bikesharing introduces e-bikes to a new audience of users who otherwise may not be familiar with the technology or have
access to it. This was implemented at the University of Tennessee, Knoxville, through an on-campus e-bike sharing system pilot project, which offers users access to both regular bicycles and e-bikes [25].

The motivation for this study stems from this introduction of new technology. Introducing e-bikes and e-bike sharing technology could influence user behaviors, which raises concerns over the impact to user safety. For instance, behaviors on shared use facilities, greenways, or bicycle paths as well as user behaviors in mixed traffic conditions can have impacts to user safety [26-30]. This study seeks to investigate the differences in behavior between users of regular bikes and e-bikes and uses the on-campus e-bike sharing system as a platform for this investigation. We focus on four key behaviors that could reduce safety, comparing e-bike rider behavior with bicycle rider behavior: 1) wrong-way riding on one-way streets, sidewalks, or two-way streets, 2) speed on shared-use paths, 3) stopping behavior at stop-controlled intersections, and 4) stopping behavior at signalized intersections. The primary objective is to objectively quantify user behavior to inform policy on an e-bike’s role in the transportation system. On one hand, we expect that e-bikes could influence more dangerous riding behavior because of increased speed. On the other hand, e-bikes could influence safer driving behavior because of improved acceleration and hill-climbing capability, prompting the rider to adhere to auto-oriented traffic control devices (e.g., stop signs on hills).

METHODS OF ANALYSIS

Recorded Trip data

Data collected through a variety of measures provide details for each trip by each user in the pilot program. These include detailed transaction logs describing user transactions from each e-bike sharing station and global positioning system (GPS) data collected from the bikes during user trips. Figure 1 identifies the location of the GPS device installed on a typical bike and e-bike in the sharing system. The component configuration of the GPS device, including the GPS data logging system (Garmin GPS18xLVX), the data collection module, and connection to the bike’s battery power, are depicted in Figure 2. GPS data consists of National Marine Electronics Association (NMEA) sentences containing date, time, position, altitude, speed, and measures of data precision and error.

GPS collection devices were installed on six regular bicycles and seven e-bikes with data collection beginning in October 2011 through December 2012. These sources provide a method for tracking system use and demand as well as providing a direct observation of user behavior and performance while operating the bikes. The GPS devices recorded data once per second after the device was initiated. For e-bikes, this process was connected to the bikes controller, turning on the GPS device when the e-bike received power. For regular bicycles, this was accomplished via a separate battery pack, which ran continuously. Data recorded for each bike type are filtered to represent only data for actual trips and to eliminate positions with poor fix quality.
Figure 1: Location of GPS Receiver on E-bike.
GIS Analysis

Collected GPS data were processed and analyzed using geographic information system (GIS) software, ArcGIS. The data were overlaid with a detailed network representing area streets, sidewalk edges, greenway facilities, and traffic signal locations. Additional layers were created to establish zones for detecting behaviors at intersection approaches and along roadways and greenways. Furthermore, annual average daily traffic (AADT) counts [31] where available and posted speed limits for roadway segments were matched to the network. Data for each recorded trip were processed into point and line layers for analysis within the network. Processed data for each trip is depicted in Figure 3. With regard to user safety, data analysis occurred over four areas: 1) user behaviors on roadways under mixed traffic conditions, 2) user behaviors on shared use facilities or greenways, 3) user behaviors at stop-controlled intersections, and 4) user behavior at signalized intersections.
Figure 3: GIS Data from Recorded Trips.

Travel on roadways

Analysis of user behaviors along roadway segments included 170 directional roadway segments, primarily in the area of the campus of the University of Tennessee, Knoxville. User movements along each roadway segment were identified and analyzed with regard to speed and direction of travel. One-way road segments were identified within the GIS network. On roadway segments allowing two-way travel, buffers were created corresponding to the lanes for travel in each direction. Directional layers were established, corresponding with the correct direction of travel on each segment. Due to GPS accuracy to accurately classify observations of bike users riding on the far right side of the road, these buffers included sidewalks or adjacent paths and extended to the centerline of the roadway. The created buffer layers were used to intersect with data points corresponding to trips along each of the roadway segments and to identify the direction of travel for each point.

Travel on shared use facilities

Similar analysis methods were applied to shared use facilities or greenways as were used for analysis on roadway segments. Buffer zones were created as overlay layers based on greenway locations. Using these overlays to intersect trip data points, trips utilizing the greenway segments were identified. Observations were analyzed across 23 greenway segments in the Knoxville area with regard to travel speed.

Analysis at Stop-Control intersections
Intersection approaches were analyzed in two categories, those with stop-control and those with traffic signals. Analysis at stop-control approaches included 76 approaches. To capture observations at stop-control intersections, buffer layers were created for each approach extending from the edge of curb at the intersecting street, across the width of the street, including the width of the sidewalk on either side of the approach, and extending 20 feet beyond the stop bar. These buffer layers were then intersected with point data corresponding to user trips to determine trips entering the intersection via the given approach. A directional layer was incorporated to exclude any observations entering the buffer layer from one of the other intersection approaches. A typical stop-controlled intersection with observed trips is shown in Figure 4.

Observations were analyzed under varying speed-based thresholds to determine stop sign violation rates. The speed thresholds served as upper limits to identify observations of stopped bicycles at each approach and the severity of violation (e.g., running a stop sign at 5 kph versus 15 kph). Bike trips with observed speeds at or below the given threshold are considered stopped and, thus, obeying the stop sign. Those observations with speeds greater than the given threshold are considered in violation of the stop sign. Both violations and non-violations were recorded to determine a violation rate for the approach.

![Figure 4: User Trips at a Stop-Controlled Intersection.](image)

**Analysis at Signalized intersections**

Similar buffer layers and directional layers were created for approaches to signalized intersections to identify observations entering the intersection via the given approach. Observations were studied at 28 signalized approaches. At approaches to signalized
intersections, additional data were incorporated to determine if movement was in violation of the traffic signal. Traffic signal timing data were obtained from the City of Knoxville Traffic Engineering Division for signalized intersections in Knoxville, TN, based on the coverage area from recorded trips. Signal timing data for intersections using fixed timing patterns were incorporated into the GIS analysis and matched to observations based on the time recorded by the observation’s GPS data and the reference time for the signal approach as given in Equation 1.

\[ \text{TIME}_{\text{Reference}} = \text{TIME} + \text{Offset} + \text{Correction} \]  

(Eq. 1)

Offset values for each signal are given by the signal timing plans. The correction factors are based on manual observations of each phase corroborated by GPS devices at the signal location and applied to correct any discrepancies in the time used by the signal controller and the actual time as shown through GPS. This approach allows second-resolution accuracy of matching bike GPS location and speed with signal phase at intersection approaches. Separate plans were created for each signal phase corresponding to the matching approach indicating whether movements are permitted or not for a given time of day (and thus signal phase).

This was used to determine first, if the observed user stopped at the signal; and second, if the user violated a red phase by not stopping. As with stop-controlled intersections, the analysis considered a range of speed thresholds to determine adherence to the traffic signal at that location. Trips that included observations with speeds below the set speed threshold were considered stopped at the intersection and not in violation of the signal. Those trips without such observations were considered potential violators of the traffic signal. Comparison to the approach timing plan identified those trips with movements that violated a red phase and those with movements that were permitted. Violation rates were calculated for each signal location and compared across bike types.

**STUDY RESULTS**

Algorithms were established in ArcGIS for analyzing user behaviors under each of the four categories. This analysis yielded results comparing user behavior in several areas of importance: travel speed, conformance to directional travel matching the roadway facility, and adherence to stop signs and traffic signals. As a result of the methods used to identify observations, other behaviors were included in some of the results.

**Travel speeds**

Travel speeds for users of both regular and electric bicycles were studied on both roadway segments, indicating travel in mixed traffic conditions, and on shared use facilities. After filtering GPS data to match user trip times, many observations contained low speed values. Observations with speeds below 2 kilometers per hour (kph) were considered stopped. This value is consistent with GPS based observations of e-bike and regular bicycle users by Cherry et al. [32]. The travel speeds for e-bike users are higher on average, 13.3 kph, than those for regular bicycle users, 10.5 kph. These values also
correspond well to observations of e-bike and regular bicycle users in China by Cherry et al. [32] and are statistically significant at a 99% confidence level.

This result fits the assumption that e-bike users are able to maintain higher travel speeds than regular bicycle users due to the increased performance of the e-bike. This could promote users to ride e-bikes on roadways more often, as opposed to on sidewalks or on other facilities. However, our surveys show that e-bike sharing system users have neutral opinions about the advantages of riding e-bikes in traffic [25].

While speed observations for both bike types are largely clustered well below 20 kph, users of both bicycle types are able to achieve much higher travel speeds. Pedal assistance on the e-bikes in this study is limited to 20 miles per hour (mph), or approximately 32 kph, corresponding to the 99th percentile of observed e-bike speeds in this study. The 85th percentile speed for e-bikes is 20 kph. For regular bicycle users, the 85th percentile speed is 17 kph and the 99th percentile is 29 kph. Average trip distance for e-bike trips is 700.4 meters (standard deviation = 492.9 meters) and for regular bicycles is 612.3 meters (standard deviation = 506.0 meters).

Posted speed limits through the area covered by these observations range from 15 mph (24.1 kph), near school zones, to 45 mph (72.4 kph). Most roadways on campus and in the area have posted speed limits of 25 mph to 35 mph, corresponding to 40 kph to 56 kph. Average travel speeds for users of either bicycle type are lower than these speed limits; yet, many users are able to travel at speeds similar to the posted speed limits.

On shared use facilities, regular bicycle users have slightly higher average travel speeds than e-bike users, 12.6 kph versus 11.0 kph respectively. They also have slightly higher average top speeds across all segments, 26.0 kph for regular bicycle users versus 25.4 kph for e-bike users. These comparisons are significant at a 95% confidence level. This could be indicative of the nature of trips and the users making those trips on greenways. Among studied bike sharing system users, 14% of regular bicycle users chose to use the sharing system because it provided a level of exercise compared to only three percent of e-bike users [25]. Higher travel speeds on these facilities for regular bicycle users could reflect the exercise nature of the trip and the physical fitness levels of the user. The importance of high travel speed observations on these facilities is the difference of those speeds with typical travel speeds of other users, in this case walking speeds that are typically 3 mph to 4 mph, or 4.8 kph to 6.4 kph. High top speeds, observed over 25 kph on average, for both bicycle types are the most concern on these segments because of the differential with walking speeds of pedestrians who share the facility. This finding also supports the notion that e-bikes should be allowed on greenways, at least to the extent that speed is a factor in the decision. E-bike riders in this study had lower average and top speeds on greenways.

Across the various shared-use facility segments, regular bicycle speed observations are more varied than e-bike speeds with some segments showing consistently low speeds and others having observations with much higher speeds, while observed e-bike speeds are more consistent between segments. Again this variation is likely reflective of the
performance characteristics of the two bicycle types, where e-bike users can more easily maintain their travel speed across rolling terrain due to the added benefit of the e-bike motor.

**Wrong way riding and other behaviors on roadway segments**

In addition to analyzing travel on the 170 roadway segments by speed, other behaviors were considered. Mainly, the focus of this analysis was to determine the rate of users of regular bicycles and e-bikes travelling in the wrong direction on roadways. This is particularly important around the e-bike sharing system stations where some of the primary roadways accessing the station site are one-way streets. This analysis, however, includes roadway segments throughout the coverage area. By the nature of the design, a portion of other violations are captured in this analysis. Observations of users traveling on sidewalk facilities, in the opposite direction of traffic flow on the roadway, are also included in the results as violations on the given roadway segment, whereas sidewalk riding in the correct direction is not a violation. Sidewalk riding in either direction in Tennessee, by bicycle and e-bike, are generally legal. Due to GPS data accuracy, it is not possible to distinguish, however, between users travelling the on the roadway and those on the sidewalk. Therefore, observations of users on the sidewalk are treated as those on the roadway are only identified as violations based on direction of travel. Wrong-way riding on sidewalks, though not illegal, is generally risky behavior.

The average violation rate by regular bicycles along these segments is not significantly different than that for e-bikes, 0.43 compared to 0.42. Violation rate comparisons with posted speed limits are also not statistically significant; however, AADT values do appear significant in some cases. Roadways with an AADT counts between 5,000 and 10,000 have higher violation rates than roadways with AADT counts between 1,000 and 5,000 as well as those with counts greater than 15,000. These comparisons are significant at an 85% confidence level. Figure 5 shows the distribution of violation rates across the range of AADT values for the roadway segments.

These violation rates may indicate that traffic volume and speed have little impact over wrong way travel by bicycle and e-bike users. More likely, these values indicate that most users are actually traveling on sidewalks, particularly when traffic volumes on the roadway make travel on sidewalks more convenient. In the previous survey of e-bike sharing system users, many users responded that they had either completed one of the studied trips using sidewalks or admitted to using sidewalks on other trips [25].
User behaviors at Stop-Control intersections

Behaviors were observed at intersections with both stop-control and traffic signals with violations of intersection control analyzed by bicycle type and under varying speed detection thresholds. The average violation rates at intersection approaches with stop-control are depicted in Figure 6. At these intersection approaches, the average violation rate is lower for e-bike users for speed detection thresholds less that 11 kph but higher beyond this threshold. This indicates that e-bike users are more likely to obey stop signs; however, those who violate the stop sign are likely to do so at a higher speed than regular bicycle users. A threshold of 11 kph is also slightly higher than the average observed travel speed for regular bicycle trips, meaning few regular bicycle users are likely to enter an intersection above this threshold even when violating the stop sign.
User Behaviors at Signalized Intersections

For signalized intersections, violation rates are lower than those observed at stop-controlled approaches; however, violation rates by e-bike users are higher at these approaches under most speed thresholds. Furthermore, the number of observations of e-bikes at signalized approaches (n=240) is considerably higher than the number of observations of regular bicycles at those approaches (n=57). This observation could reflect that many regular bicycle users avoid signalized intersections or that, because of the performance of e-bikes, more of those users are likely to take routes that encounter signalized intersections. This could reflect an increased perception of safety on e-bikes than on regular bicycles while traveling through intersections.

Based on the average violation rates, detection thresholds of 3 kph or less consistently result in very high violation rates at both intersection approach types. Lower threshold values likely represent speeds too low for accurate detection of stopped vehicles with the given GPS data quality. Above this speed threshold, there is much variation among violation rates for regular bicycles and e-bikes at both types of intersections.
Among the intersection approaches studied, there is much variation in violation rates, some with very high violation rates and others with relatively low rates. A number of variables were considered as potential factors influencing violation rates at each location: AADT for the approach and for the intersecting roadway; posted speed limits for both the approach and intersection roadway; whether the slope of the approach is uphill, downhill, or level; as well as bicycle type, either regular bicycle or e-bike. An ordinary least squares regression model, of the form presented by Equation 2, including these variables was fitted to investigate the impacts of each variable of on violation rates ($V_{Rate}$) at the intersections. Model parameters are described in Table 1.

$$V_{Rate} = \beta_0 + \sum_{i=1}^{n} \beta_i x_i \quad (Eq. 2)$$

Considering all approaches, the approach type, posted speed limit and AADT of the approach and intersecting street, and interactions between AADT and posted speed are significant factors contributing to violation rates. For stop-control intersections, these factors are intersecting AADT, approach grade entering the intersection, and interaction between approach and intersecting street AADT counts. Signalized intersections are again different, with important factors of approach AADT, posted speed limits for the approach and intersecting street, as well as interactions for the approach and intersecting street AADT and posted speed limits.
### Table 1: Models for Violation Rates at Intersection Approaches.

<table>
<thead>
<tr>
<th></th>
<th>All Approaches*</th>
<th>Stop-Control**</th>
<th>Signalized***</th>
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<tbody>
<tr>
<td></td>
<td>Parameter Estimate</td>
<td>Pr &gt;</td>
<td>t</td>
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<tr>
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<tr>
<td>AADT*Speed</td>
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</table>

*R-Square = 0.4441.
**R-Square = 0.1120
***R-Square = 0.4145

These models suggest that approach slope and intersecting traffic volumes have more bearing on violation rates at stop-control intersections than signalized ones. A negative value for approach grade indicates that a downhill slope promotes more stop sign violations than an uphill slope. Significant factors of approach AADT and posted speed limit for signalized intersections indicates that the approach environment itself is highly important at those intersections.

One important factor that does not enter any model is bicycle type. Approach type, on the other hand, is significant. This indicates that while behaviors are different between users of each bicycle type the performance differences between the two modes are not significant factors to safety at intersections. The characteristics of the intersection itself, however, are significant factors to user safety. While the factors included in these models were found to be significant, low R-Square values for each model indicate that additional factors are important, highlighting a need for additional research into facility characteristics and user safety.

### DISCUSSION AND CONCLUSIONS

This research investigates user safety on two modes that share many similar characteristics but differ in terms of performance, regular bicycles and e-bikes. Concerns over user safety on e-bikes as compared to regular bicycles stems from the added benefit that users gain from the electric motor on e-bikes, which raise important policy questions about the differential role and place of e-bikes in the transportation system. In this study we considered several factors that have relevance to user safety: speed on roadways and
shared use facilities, behaviors at intersections, and wrong way travel. While differences in behavior exist, and these differences have bearing on overall user safety while operating the two bicycle types, the differences are generally small and generally explained by other factors, unrelated to the bike itself. This infers that the advantages that users gain from e-bikes have little overall effect on user safety as compared users of regular bicycles. For instance, violation rates at intersections differ between the two modes, but the larger difference occurs between intersection types, not bicycle types.

These findings have relevance to bicycle and e-bike policy, mainly in removing a misconception that e-bikes are intrinsically more dangerous than regular bicycles. Violation rates were generally high for both modes. Further, this study identifies some areas for future research in understanding safety for users of the two modes. User performance on the two modes varies by facility type and facility characteristics. Additional characteristics such as the presence of bicycle lanes and other bicycle related facilities could curb dangerous user behavior, and reduce violations, by promoting safer practices among bicycle users.

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