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Naturalistic Vehicle-Bicycle Interactions in Urban Environments

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By

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16. Abstract

In the United Sates, the number of bicyclists killed in traffic crashes and rates have significantly increased over the years. The majority of bicyclist fatalities occur in urban areas, non-intersection facilities, and during dawn, dusk, or night conditions. The most prevalent vehicle-bicycle fatal crash types involve motorists overtaking bicyclists, and vehicles and bicycles following parallel paths. Since roadway geometry and operations significantly influence driver behavior when passing bicyclists, it is critical to investigate the safety of bicyclists on urban multilane and single lane roadway arterials. A bicycle naturalistic study was conducted to examine driver passing behavior and bicyclist safety on five different urban roadway arterial configurations. Roadway configurations had variations in the number of lanes, median type, and bicycle buffer. Median types included two-way left turn lane (TWLTL), hatched, and undivided medians. This is the first study to evaluate the effect of different median designs on urban single lane roadway arterials. Data from 679 naturalistic observations were collected in the cities of Madison and Fitchburg, Wisconsin. Performance measures included passing lateral distance, passing speed, adjacent lane encroachment, centerline encroachment, and crowding. Regression analysis was implemented to assess the effect of roadway operational and operational conditions on performance measures. Median type, the presence of adjacent or opposing traffic, and large vehicles had statistically significant effects. The TWLTL median with two lanes and non-buffered bicycle lanes, had the largest mean lateral distances among all roadway configurations. The bicycle buffer seems to proportionally increase the passing lateral distance on single lane configurations. On the multilane roadway configuration, adjacent traffic reduced the propensity of greater extents of adjacent lane encroachment while passing a bicyclist riding in the bicycle lane. In terms of single lane configurations, the presence of opposing traffic reduced the propensity of centerline or median encroachment. TWLTL and hatched medians increased the propensity of median encroachment compared to the roadway with undivided median. Regarding vehicle type, larger vehicles had a reduced passing lateral distance compared to passenger vehicles. Passing speeds were lower with a raised median, adjacent or opposing traffic. The presence of adjacent (multilane) or opposing (single lane) traffic increased the propensity of crowding. Median type did not have a statistically significant effect on crowding at single lane configurations; however, these sites either had wider traversable medians or buffered bicycle lanes which provided greater available space for passing vehicles.

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1. INTRODUCTION

Bicyclists are more vulnerable to sustain severe injuries in collisions with motor vehicles because of the proximity of operating spaces and lack of protective enclosure. In the United States, the number of bicyclists killed in traffic crashes has increased from 829 fatalities in 2015 to 1,103 fatalities in 2024. Fatality rates were 0.25 and 0.32 per 100,000 population, respectively (NHTSA 2026). Of all bicyclist fatalities, 81% were in urban areas (IIHS and HLDI 2026), 60% at non-intersection locations, and 56% were during dawn, dusk, or night conditions (NHTSA 2026). The most prevalent vehicle-bicycle fatal crash type (28% of all crash types) involved motorists overtaking bicyclists. The second most common crash type consisted of vehicles and bicycles following parallel paths, which accounted for 9% of fatal crashes (Thomas et al. 2019). Roadway geometry and operations significantly influence driver behavior when passing bicyclists. Therefore, it is critical to investigate the safety of bicyclists on urban multilane and single lane roadway arterials, which have higher speed limits than local streets.

A bicycle naturalistic study was conducted to examine driver passing behavior and bicyclist safety on five different urban roadway arterial configurations with variations in the number of lanes, median type, and bicycle buffer. This is the first study to evaluate the effect of different median types on urban single lane roadway arterials. Data from 679 naturalistic observations were collected in the cities of Madison and Fitchburg, Wisconsin. Measures evaluated included passing lateral distance, passing speed, adjacent lane encroachment, centerline encroachment, and crowding. Crowding is a passing event in which the lateral distance between a motor vehicle and a bicyclist is sufficiently small to impact the bicyclist's operation. Roadway geometric and operational variables were modeled to quantify the effect on bicyclist safety.

2. LITERATURE REVIEW

2.1 Lateral Distance

Passing lateral distance refers to the distance between the right side of the vehicle and the left side of the bicycle. Roadway geometric and operational elements impact lateral passing distance. In terms of geometric elements, the effect of number of motor vehicle lanes, width of lanes, bicycle buffers, and street parking were reviewed. Regarding operational effects, traffic volume, adjacent or opposing traffic, vehicle type were covered.

Wider lanes have been associated with greater lateral distances when vehicles pass bicycles (Love et al. 2012). Love et al. (2012) evaluated the lateral passing distance between vehicles and bicycles on urban one-way multilane roadways with bicycle lanes and parking in Baltimore, Maryland. Wider lanes resulted in greater passing lateral distances. Passing lateral distances ranged between 48–120 in (120–300 cm) and the mean passing lateral distance was approximately 72 in (180 cm) with 11 ft (3.3 m) lanes. In a study conducted with data from multiple cities in Australia, Nolan et al. (2021) evaluated the total width of the vehicle lane and the bicycle lane and found that wider vehicle-bicycle lane widths tended to have larger average passing distances, and fewer passing events were less than 3.3 ft or 39.6 in (1.0 m).

The number of lanes plays a significant role in the available space when vehicles pass bicycles. However, the presence of adjacent traffic in multilane roadways or opposing traffic in single lane roadways has the most significant effect reducing the available space and consequently the passing lateral distance. On multilane roadways, close vehicle passing maneuvers were significantly higher than on single lane roads (Mehta et al. 2015; Nolan et al.

2021). Mehta et al. (2015), a study conducted with data from several cities in Canada, concluded that encroachment or lane change was impacted by the proximity of vehicles in the adjacent lane. When drivers on four-lane roadways without bicycle lanes were restricted from encroaching or changing lanes, the passing lateral distance tended to be smaller, and a higher proportion of passing maneuvers were unsafe, less than 3.3 ft or 39.6 in (1.0 m) (Mehta et al. 2015). Nolan et al. (2021) indicated that these occurrences may be attributed to an increased difficulty for drivers to check the adjacent lane traffic and change lanes to overtake the bicyclist than to look forward into oncoming traffic. Similarly, Sando and Moses (2011) and Evans et al. (2018) found that the presence of a vehicle in the adjacent lane played a significant role in reducing the passing lateral distance. In terms of single lane roadways, the presence of opposing traffic reduces passing lateral distance as well. Shackel and Parkin (2014) studied driving behavior when passing bicyclists on urban single lane roadways with 20 and 30 mph (32 and 48 kph) speed limits in the United Kingdom. Greater passing lateral distances were observed when opposing traffic was farther away than when opposing traffic was closer or alongside the passing vehicle (Shackel and Parkin 2014). On a test track experiment, Rasch et al. (2020) specifically examined the influence of oncoming traffic and bicyclist lane position on passing lateral distance. Subjects overtook a robotic bicyclist dummy riding at two different lateral positions within the lane. An oncoming balloon robotic vehicle was triggered to meet the subject's test vehicle when passing the bicyclist with either 6 or 9 s time-to-collision (TTC). Safety measures evaluated included TTC to rear-end and sideswipe with the bicyclist, and head-on collision with opposing traffic. The results showed that when the time gap to the opposing vehicle was shorter, safety measures for all potential collisions decreased. In a semi-naturalistic study conducted in urban roads in Braunschweig, Germany, Strelow and Vollrath (2026) found that with the presence of opposing traffic, drivers tend to reduce passing lateral distances, which may be attributed to space constraints and concerns about head-on collisions.

Vehicle type also has a significant impact on passing lateral distance. Walker (2007) conducted a naturalistic study in the United Kingdom and evaluated passing maneuvers and the relationship with bicyclists and vehicle characteristics. Walker (2007) found that drivers of large vehicles (buses and heavy goods vehicles), on average, passed bicyclists closer than drivers of passenger vehicles. Nolan et al. (2021) indicated that large vehicles tend to overtake bicycles at 6.6 in (16.9 cm) closer than passenger vehicles, and large vehicles were 5% more likely to pass closer than 3.3 ft or 39.6 in (1.0 m). When compared to sedan passenger vehicles, the median passing lateral distance of buses was reduced by 11 in (28 cm) (Beck et al. 2019). Strelow and Vollrath (2026) found similar results; larger vehicles such as trucks and buses maintained a reduced passing lateral distance than passenger vehicles, which was accentuated with the presence of opposing traffic. In terms of bicyclist risk perception with large passing vehicles, bicyclists felt less safe (Beck et al. 2021; Strelow and Vollrath 2026; Llorca et al. 2017) and had weaker stability (Chuang et al. 2013). In a controlled study in a laboratory setting, experienced bicyclists rode on free rollers (pedaling but longitudinally stationary) while being passed by large semi-trucks (length: 54.1–106.6 ft, 16.5–32.5 m) at 31 and 50 mph (50 and 80 kph). The results of the study showed that the largest impact on bicyclist aerodynamic load and discomfort rating was passing lateral distance, followed by passing speed (Kircher et al. 2025). Using field testing, computational fluid dynamic simulations, and wind tunnel experiments, Madkour et al. (2023) found that aerodynamic forces on bicyclists during passing maneuvers substantially increased

with large vehicles, speed, and proximity. For instance, semi-trailers produced flipping moments exceeding the 17 N recommended threshold under nearly all tested conditions (FHWA 1977; Madkour et al. 2023).

Bicycle lane buffers are the additional space separating vehicle and bicycle lanes delineated with solid edgeline and diagonal crosshatched pavement markings. In a bicycle naturalistic experiment, with lateral passing distances less than 100 in (254 cm), the mean passing lateral distance was 77 in (196 cm) with buffered bicycle lanes compared to 62 in (157 cm) with non-buffered bicycle lanes (Evans et al. 2018). Similarly, Nolan et al. (2021) showed that the average passing distance was 14 in (37 cm) greater with buffered bicycle lanes (81 in, 207 cm) than conventional non-buffered bicycle lanes (67 in, 170 cm). In a study conducted in Fort Lauderdale, Florida, the passing lateral distance with buffered bicycle lanes was 69 in (175 cm), while the passing lateral distance with the traditional bicycle lanes was 60 in (152 cm), a difference of 9 in (23 cm). The buffered bicycle lane was 72 in (183 cm) versus 60 in (152 cm) wide for the traditional bicycle lane (Sando and Hunter 2014). Dadashova et al. (2025) developed crash modification factors (CMF) for on-street bicycle facilities. Using data from Philadelphia Pennsylvania, the safety effectiveness results showed that installing bicycle lanes on roadways without bicycle lanes reduced bicycle crashes by 67%. When buffered bicycle lanes were installed on roadways without bicycle lanes, bicycle crashes reduced by 77%. Buffered bicycle lanes were more effective in reducing bicycle crashes than conventional bicycle lanes.

2.2 Passing Speed

Roadway geometry and traffic operations can influence vehicle passing strategy and speed. Passing strategies include flying and accelerative maneuvers. A flying strategy consists of the passing vehicle maintaining a constant or nearly constant speed throughout the entire passing maneuver without slowing down. An accelerative strategy consists of the vehicle approaching and slowing down or temporarily remaining behind another vehicle or bicycle before accelerating to complete the passing maneuver. For both flying and accelerative passing strategies, the manner in which the passing vehicle returns to the travel lane can be further classified as either a forced or voluntary return, depending on the proximity of oncoming traffic (Matson and Forbes 1938). Flying maneuvers (79%) were more prevalent than accelerative maneuvers (9%), and flying maneuvers were performed with higher speeds and lower lateral clearances (Moll et al. 2021). Claros et al. (2026) found that vehicle passing speed according to the position in the platoon had a decreasing trend. The farther back the follower vehicle was in the platoon, the lower its passing speed. The difference in mean passing speed from the leading vehicle compared to a follower vehicle in the fourth position in the platoon was 2.5 mph (4.0 kph) with no opposing traffic and 3.5 mph (5.6 kph) with opposing traffic.

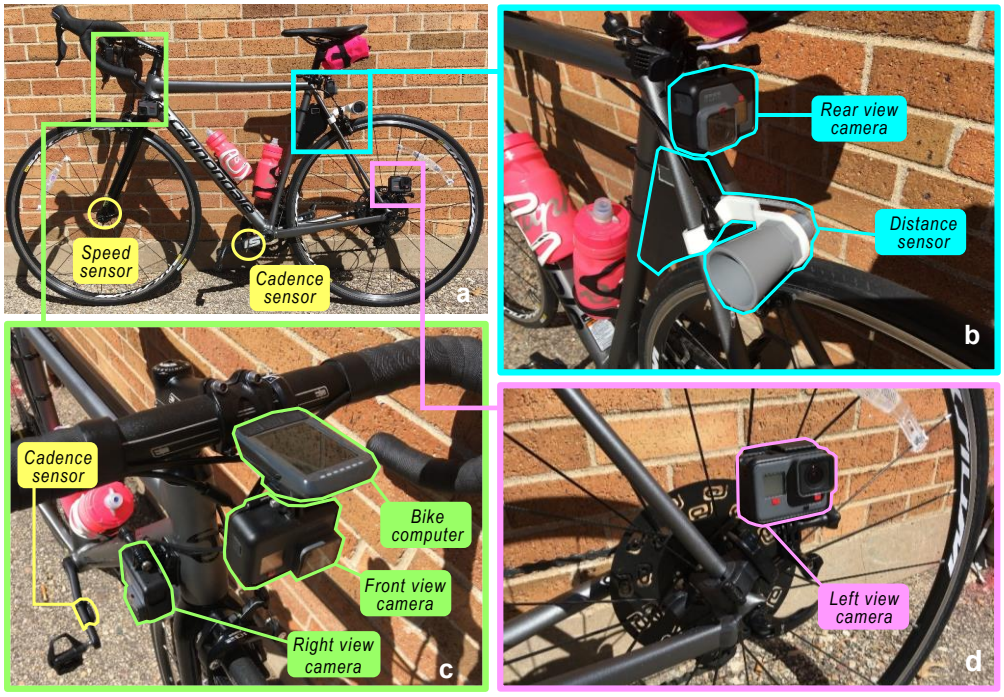
Urban arterials have higher speed limits (30–45 mph, 48–72 kph) than residential or local streets (20–30 mph, 40–48 kph). Speed is a major factor in bicyclist safety on urban arterials because of the transfer of kinetic energy, which influences the severity of injuries bicyclists can sustain. For instance, if a bicycle were traveling at 12 mph (19 kph) and a passenger vehicle at 45 mph (72 kph), the relative speed between the bicycle and vehicle would be 33 mph (53 kph). At this impact speed, the estimated risk of severe injury or death would be approximately 50% and 25%, respectively (Tefft 2013). The risk of injury or death significantly increases with larger vehicles and bicyclists' age (Tefft 2013; Bahrololoom et al. 2020). Thus, bicyclists' exposure to higher vehicular speeds is of concern.

In a driving simulator study, Pirdavani et al. (2026) studied driving behavior when passing bicyclists in different urban roadway configurations with bicycle infrastructure. Roadway configurations included one-way and two-way cycle streets, advisory bicycle lanes (suggested bicycle lanes, vehicles are allowed to use when necessary), and adjacent bicycle lanes (legally reserved for bicycle operations). Cycle streets were defined as streets where bicycles are the primary mode of transportation, and motorized vehicles have limited access and lower priority. Motor vehicles are not allowed to overtake in cycle streets. Two-way cycle streets were the most effective in reducing the passing speed. The presence of adjacent cycle lanes did not result in significant reductions in passing speed (Pirdavani et al. 2026).

3. METHODOLOGY

3.1 Bicycle Instrumentation

A road bicycle was instrumented with video cameras, geolocation device, microprocessors, and sensors (rider heart rate, speed, cadence, and lateral distance) (Claros et al. 2024, 2026). To maintain the realism of a traditional road bicyclist on the roadway, the devices had minimal visibility and weight. Most devices were readily available commercially; however, the distance sensor hardware and software were developed and integrated to collect and store data. Figure 1 illustrates the instrumented bicycle with the different devices and sensors mounted on the bicycle. Data was collected in different hardware, sensor, and video formats, so synchronization and integration of the data were required.



Notes: a. left side of bicycle with all sensors and cameras, b. rear facing camera and distance sensor c. front facing camera, bike computer, right facing camera, and cadence sensor, d. left facing camera.

Figure 1. Instrumented bicycle. (Claros et al. 2026).

Four GoPro cameras were mounted at strategic locations on the bike to cover all 360° horizontal field of view around the bicycle in motion (cameras facing front, rear, left, and right).

The geolocation device was a Wahoo bike computer with capabilities to record location of the trajectory of the bicycle. The bike computer also recorded the rider's heart rate, bicycle speed, and cadence sensor data. The speed sensor was located on the front wheel axel and the cadence sensor was mounted on the left pedal crank arm. The distance sensor and microprocessor were located in the rear part of the bicycle frame.

The distance sensor consisted of a sonar range finder MB7040 (beam range of 24.6 ft, 750 cm long and 1.9 ft, 60 cm wide, 10 Hz rate, accuracy 1–3 %), Arduino Uno microprocessor, Adafruit data logging shield, liquid crystal display (LCD) screen, 600mAh lithium-ion rechargeable battery, and memory secure digital (SD) card. The communication protocol to integrate the different electronic components consisted of an Inter-Integrated Circuit (I2C) to collect, store, and display (on LCD screen) lateral distance data in real time and sequenced with a running clock. The distance sensor was activated when it detected a vehicle passing up to 24.6 ft (750 cm) from the left side of the bicyclist. Measurements were recorded ten times per second, which guaranteed several measurements depending on the operating speed of the passing vehicle.

3.2 Video, Location, and Sensor Data Integration

Since data is generated using multiple video and sensor devices, data needs to be synchronized, overlaid, and integrated. The result of the data integration is provided in a video format with all the data as illustrated in the screenshot in Figure 2, in which the front view is in the top right corner, rear view is in the top left corner, right view is in the bottom right corner, and left view is in the bottom left corner. Data is integrated in multiple steps with video editing, video effects processing, and Exchange Format files (GPX) processing software.



Note: a. rear facing video; b. front facing video with overlaid latitude/longitude coordinates, direction, route map, distance, grade, bicycle speed, pedal cadence, and cyclist's heart rate; c. rear facing video with overlaid lateral distance (in cm) from right side body of vehicle to the bicycle left handlebar; d. right facing video. Lacy Rd, Fitchburg, Wisconsin.

Figure 2. Bicycle naturalistic data integration.

3.3 Study Sites

Study sites were selected to evaluate single and multilane urban roadways with different operational and geometric configurations. Three sites with five different configurations were

selected in the cities of Madison and Fitchburg, Wisconsin. Table 1 provides detailed information of the study sites and Figures 3–4 illustrate the different roadway configurations.

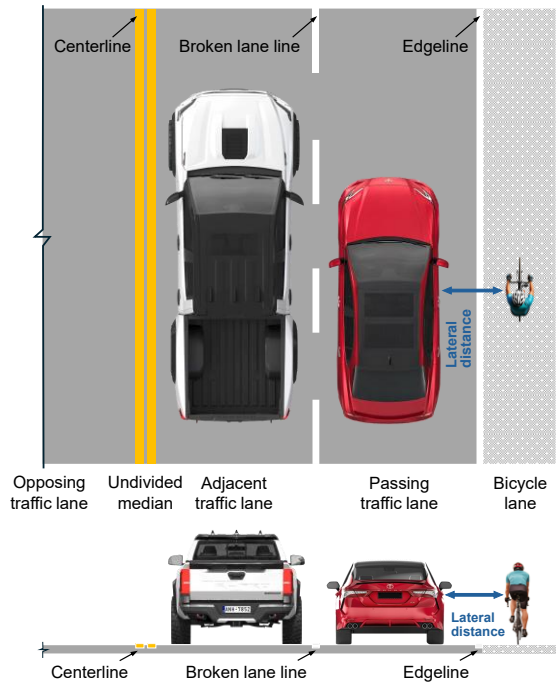
Table 1. Description of study sites.

Location and description	Fish Hatchery Rd Madison, WI	Rimrock Rd Fitchburg, WI	Lacy Rd Fitchburg, WI		
Site	FH	RR	LA-1	LA-2	LA-3
Speed limit (mph)	30	35	35	35	35
Segment length (mi)	0.4	0.3	0.6	0.5	0.2
Number of lanes	4	2	2	2	2
Median type[1]	UND	TWLTL	HM	UND	RM
Median width (ft)[2]	N/A	14	2–10	N/A	7–17
Vehicle lane width (ft)	11	11	10	10	11
Bicycle lane width (ft)	4	4	4	4	4
Bicycle buffer (ft)	0	0	2	2	2
Gutter (ft)	1	2	1	1	1

Notes: [1] UND = undivided, TWLTL = two-way left turn lane, HM = hatched median, RM = raised median; [2] constant or range of available median widths is provided. None of the configurations had vehicle parking. N/A = not applicable.

3.3.1 Urban Multilane Undivided Roadway with Non-buffered Bicycle Lanes

The segment was located at Fish Hatchery Rd in the City of Madison, Wisconsin. The posted speed limit was 30 mph (48 kph). The roadway was an undivided straight segment 0.4 mi (0.6 km) long with two vehicular lanes and a bicycle lane in each direction. Vehicle lane width was 11.0 ft (3.3 m), bicycle lane width was 4.0 ft (1.2 m), and there was no buffer between the vehicle and bicycle lanes. The gutter at the edge of the road was 1.0 ft (0.3 m) wide. The study site was coded as FH, and Figure 3 illustrates the roadway configuration.



Notes: Lateral distance between passing vehicle right side body and bicycle's left side handlebar. Not to scale.

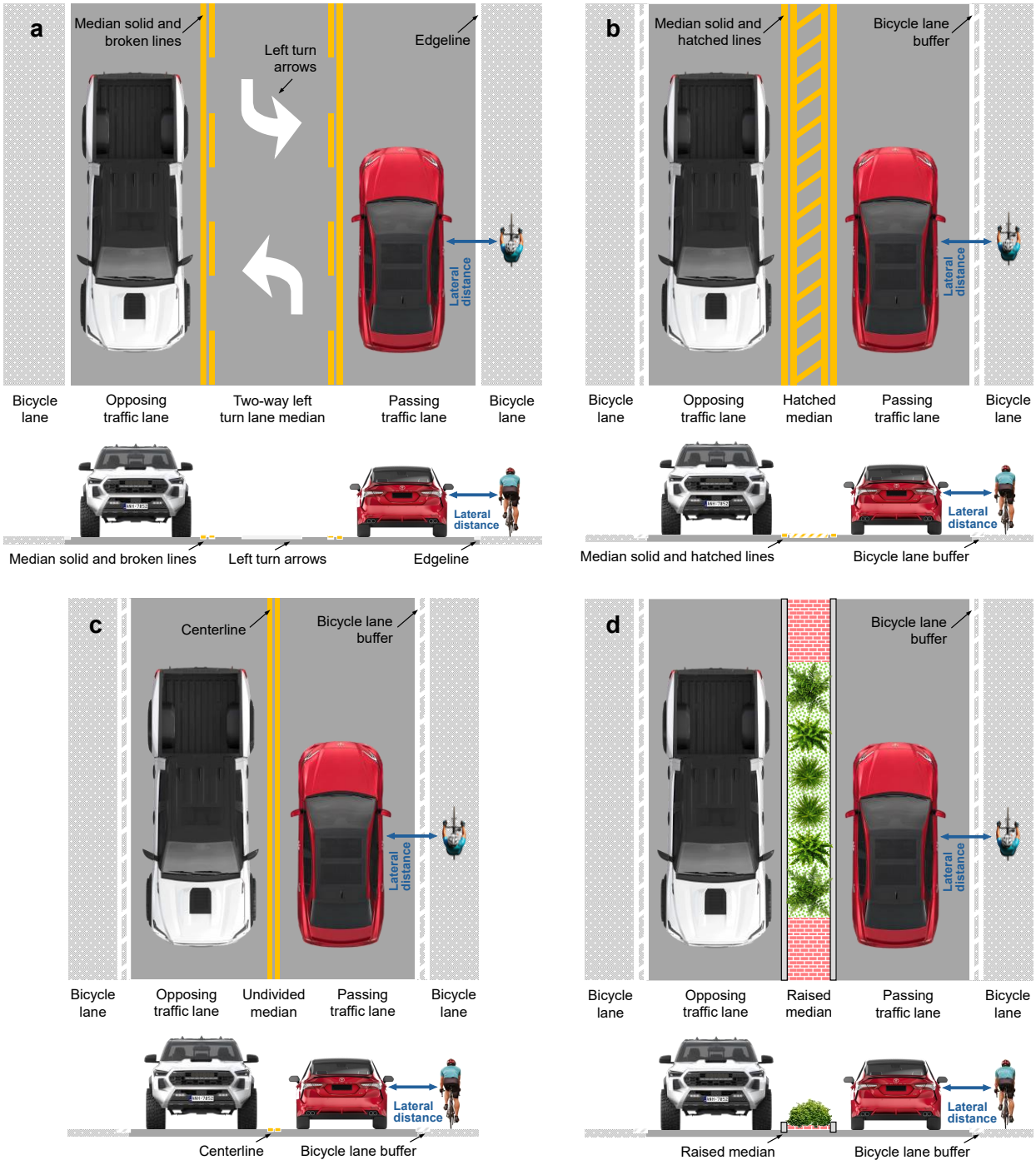
Figure 3. Urban multilane roadway with undivided median and non-buffered bicycle lanes, Site FH.

3.3.2 Urban Two-lane Roadway with Two-way Left Turn Median and Non-buffered Bicycle Lanes

The segment was located at Rimrock Rd in the City of Fitchburg, Wisconsin. The posted speed limit was 35 mph (56 kph). The roadway was a straight segment of 0.3 mi (0.5 km) with a Two-Way Left Turn (TWLTL) median, one vehicular lane and a bicycle lane in each direction. The TWLTL median width was 14.0 ft (4.3 m), vehicle lane width was 11.0 ft (3.3 m), bicycle lane width was 4.0 ft (1.2 m), and there was no buffer between the vehicle and bicycle lanes. The gutter at the edge of the road was 2.0 ft (0.6 m) wide. The study site was coded as RR, and Figure 4a illustrates the roadway configuration.

3.3.3 Urban Two-lane Roadway with Hatched Median and Buffered Bicycle Lanes

Lacy Rd in the City of Fitchburg, Wisconsin contained several roadway configurations with hatched, undivided, and raised medians. The posted speed limit was 35 mph (56 kph). Thus, the combined portions of the roadway segment with a hatched median (HM) were 0.6 mi (1.0 km), and the roadway configuration consisted of one vehicular lane and a bicycle lane in each direction. The hatched median width was between 2.0–10.0 ft (0.6–3.0 m), vehicle lane width was 10.0 ft (3.0 m), bicycle lane width was 4.0 ft (1.2 m), and there was a buffer between the vehicle and bicycle lanes of 2.0 ft (0.6 m). The gutter at the edge of the road was 1.0 ft (0.3 m) wide. The study site was coded as LA-1, and Figure 4b illustrates the roadway configuration.



Notes: a. two-lane roadway with two-way left turn (TWLTL) median and non-buffered bicycle lane, Site RR; b. two-lane roadway with hatched median and buffered bicycle lane, Site LA-1; c. two-lane roadway with undivided median and buffered bicycle lane, Site LA-2; d. two-lane roadway with raised median and buffered bicycle lane, Site LA-3. Lateral distance between passing vehicle right side body and bicycle's left side handlebar. Not to scale.

Figure 4. Single lane roadway configurations.

3.3.4 Urban Two-lane Roadway with Undivided Median and Buffered Bicycle Lane

Parts of the Lacy Rd (35 mph, 56 kph speed limit) in the City of Fitchburg, Wisconsin, had an undivided median (UND) with a combined length of 0.5 mi (0.8 km), and the roadway configuration consisted of one vehicular lane and a bicycle lane in each direction. Vehicle lane width was 10.0 ft (3.0 m), bicycle lane width was 4.0 ft (1.2 m), and there was a buffer between the vehicle and bicycle lanes of 2.0 ft (0.6 m). The gutter at the edge of the road was 1.0 ft (0.3 m) wide. The study site was coded as LA-2, and Figure 4c illustrates the roadway configuration.

3.3.5 Urban Two-lane Roadway with Raised Median and Buffered Bicycle Lane

Sections of Lacy Rd (35 mph, 56 kph speed limit) in the City of Fitchburg, Wisconsin, with a raised median (RM) had a combined length of 0.2 mi (0.3 km), and the roadway configuration consisted of one vehicular lane and a bicycle lane in each direction. The raised median width was between 7.0–17.0 ft (2.1–5.2 m), vehicle lane width was 11.0 ft (3.3 m), bicycle lane width was 4.0 ft (1.2 m), and there was a buffer between the vehicle and bicycle lanes of 2.0 ft (0.6 m). The gutter at the edge of the road was 1.0 ft (0.3 m) wide. The study site was coded as LA-3, and Figure 4d illustrates the roadway configuration.

3.4 Data Collection and Processing

One bicyclist rode (in the middle of the bicycle lane) the instrumented bicycle through predetermined routes to cover the study sites. The bicyclists rode 74 times through Site FH and 20 times through Sites RR and LA. Once the data from the different devices were integrated, data processing consisted of watching the integrated video and recording timestamps in milliseconds when vehicles passed the bicyclist and variables of interest in each interaction, including vehicle-bicycle lateral distance, presence of opposing vehicles (not present or present), vehicle lane position, passing vehicle type (passenger or heavy vehicle), passing vehicle approach type (lead or follower), and roadway geometric and operational features. The data were recorded in a spreadsheet with corresponding codes, legend, and format for every variable that would be easily manageable in data analysis and modeling.

3.5 Evaluation Metrics

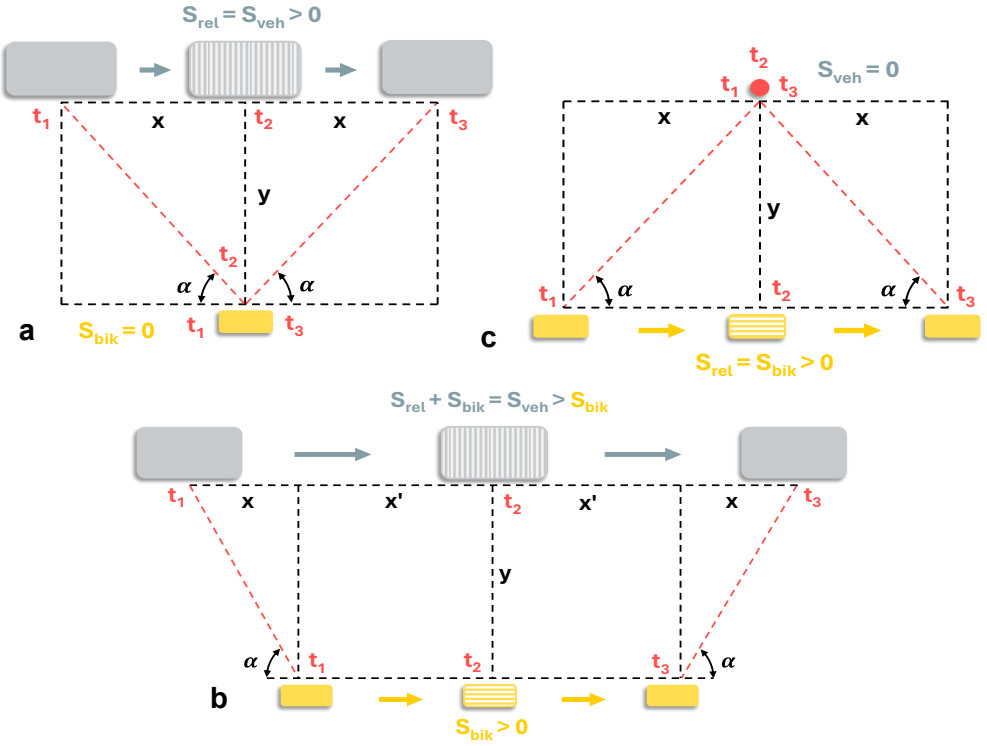
Passing lateral distance, passing speed, adjacent lane encroachment, centerline encroachment, and crowding were evaluated to assess the effect of roadway operational and geometric variables. Variables explored included number of lanes (single- and multi-lane), median type, vehicle lane width, presence of bicycle lane buffer, adjacent or opposing traffic, leading or following vehicle.

3.5.1 Passing Lateral Distance

Passing lateral distance is the minimum passing distance between the right-side body of the passing vehicle and the left side of the bicycle handlebar. The lateral distance was captured when the passing vehicle was parallel and closest to the bicycle during the passing maneuver. The passing lateral distance is illustrated in Figures 3–4 for each roadway configuration evaluated. Since the distance sensor was mounted in the rear frame of the bicycle and at a different lateral projected position than the left side of the bicycle handlebar, the difference in projected lateral distance was adjusted to have the passing lateral distance in reference to the bicycle left side handlebar. Similarly, for estimation of vehicle passing speed, the difference in the projected lateral position of the sensor in relation to the camera lens was accounted for.

3.5.2 Passing Speed

The speed of passing vehicles was estimated using the passing lateral distance, vehicle travel time through the left facing camera field of view, and bicycle speed. Since the travel time of vehicles through the camera field of view was relatively short, it was assumed that vehicle trajectory, lateral distance, and speed were constant during the period of observation. Based on these assumptions and with the use of trigonometry and constant motion physics theory, the speed of passing vehicles was estimated relative to the bicycle speed. Figure 5 illustrates the processes to derive and validate the passing vehicle speed. Figure 5a illustrates a scenario in which a vehicle passes a stationary bicycle and how the vehicle enters/exits the left facing camera field of view. Since the bicycle is stationary, the vehicle speed is the same as the vehicle relative speed. In the scenario of Figure 5b, a vehicle passes a moving bicycle, so the vehicle speed is estimated with the relative speed. Since the bicycle is moving at a known speed, the vehicle passing duration is extended. The additional vehicle passing time results in an additional passing distance, which is a function of the bicycle speed, and all other parameters are known, the vehicle speed is the relative speed plus the bicycle speed.



Notes: a. moving vehicle passing a stationary bicycle; b. moving vehicle passing a moving bicycle; c. moving bicycle passing a stationary wall marker representing a stationary vehicle (Claros et al. 2026).

Figure 5. Passing vehicle speed estimation.

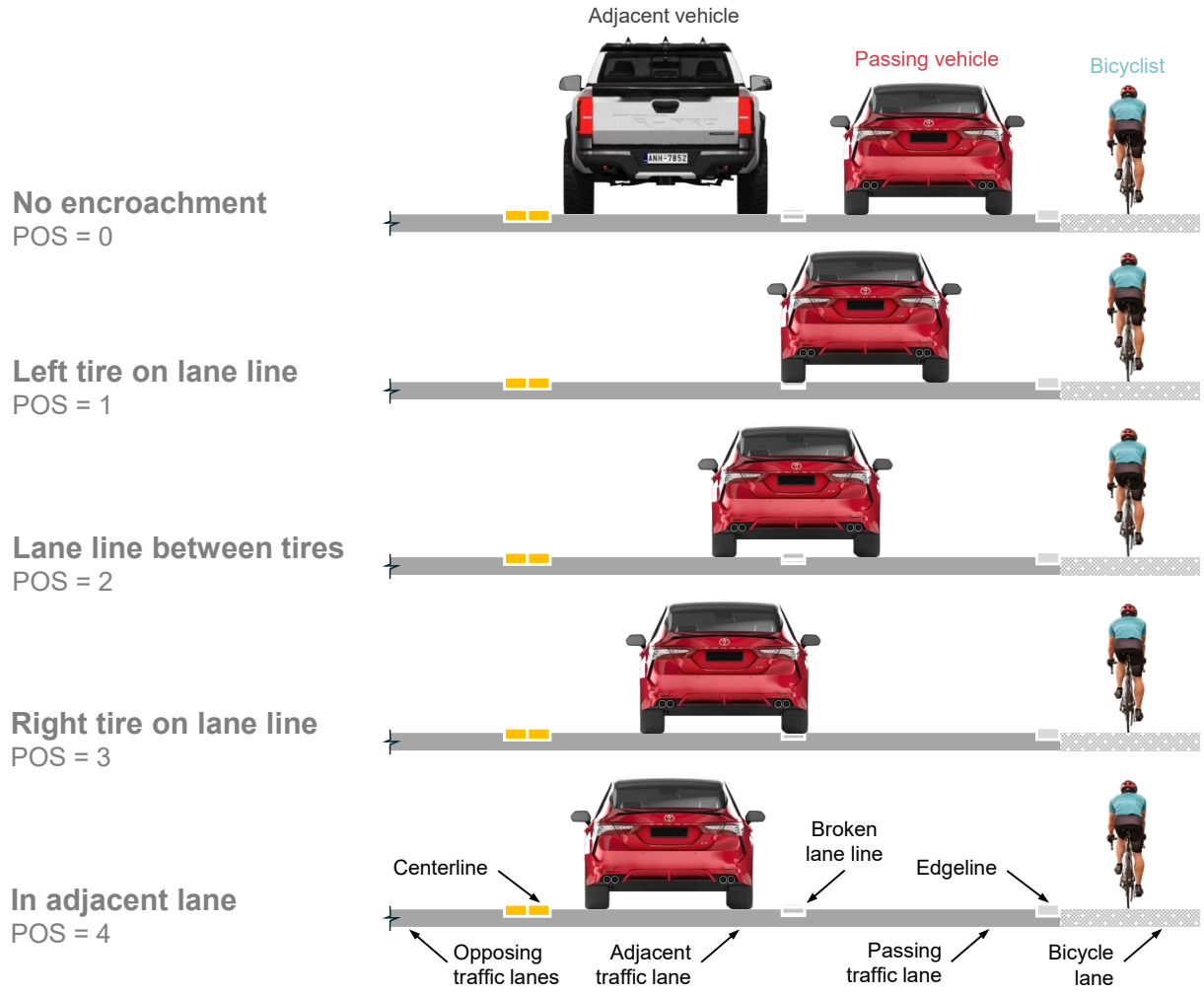
In Figure 5c, a stationary object (marker on retaining wall) and a moving bicycle were used for validation and assessment of the accuracy of vehicle speed estimates. The bicycle speed was estimated based on the lateral distance between the bicycle left handlebar and the retaining wall and time the maker was visible in the left facing camera field of view. Also, the bicycle speed was recorded with the bicycle GPS/sensor speed. Since the marker on the retaining wall was stationary, the calculated bicycle relative speed was compared to the bicycle speed from the

GPS/sensor. Speed estimates were found to have an average error difference with the GPS/sensor speeds of ±0.6 mph (0.9 kph), showing a high degree of accuracy. The validation process was conducted in a controlled scenario in which only the bicycle was in motion, so there may be other factors such as fluctuation in the position of bicycle and vehicle, or GPS/sensor precision that could influence the accuracy of the speed estimates. More details of the derivation and validation of passing vehicles speeds may be found in Claros et al. 2026.

3.5.3 Adjacent Lane Encroachment

Applicable to multilane roadways, adjacent lane encroachment is defined as the passing vehicle tires contacting or going over the broken lane line. Adjacent lane encroachment is relevant to the study of bicycle safety because at multilane roadways the presence of adjacent traffic may limit the available space and impact driving behavior with regards to vehicle lane positioning and passing lateral distance from bicycles. Vehicle position and adjacent lane encroachment was extracted from video from different angles when the vehicle was in parallel to the bicyclist. Figure 6 illustrates the five different extents of encroachment considered in this study. POS=0 consists of the vehicle remaining within the travel lane and not contacting the broken lane line with the vehicle's tires. POS=1 represents the vehicle's left-side tires contacting the broken lane line. POS=2 shows the broken lane line between the vehicle's left-side and right-side tires. POS=3 indicates the vehicle's right-side tires contacting the broken lane line. In POS=4 the vehicle has completely crossed over the broken lane line and is traveling in the adjacent lane.

Modeling of adjacent lane encroachment (POS) was conducted using ordinal logistic regression to assess the effect of vehicle type (passenger or large vehicle, VH), lead or follower vehicle (FOL), and adjacent traffic (AT). Response ordinary variables consisted of encroachment according to the different categories (POS=1–4) and no encroachment (POS=0). The presence of adjacent traffic was defined as the time headway when an adjacent vehicle was 3 s or less from the bicyclist at the time when the passing vehicle was in parallel to the bicyclist (Yang et al. 2019; Jokhio et al. 2023). A vehicle was considered to be in a following state when the time headway with the vehicle in front was equal to or less than 5 s (NASEM 2022).



Note: Not to scale.

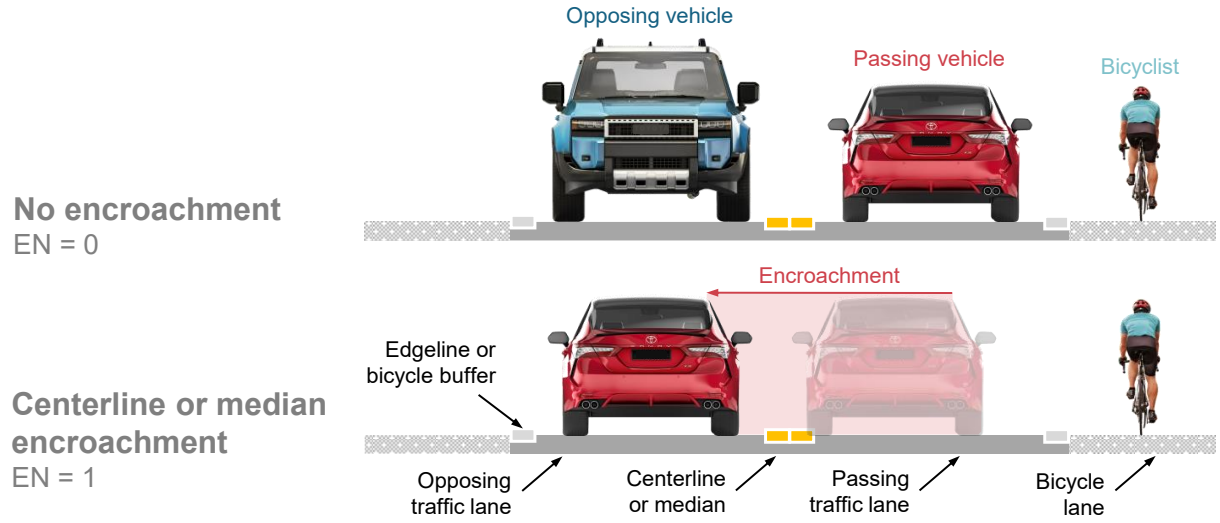
Figure 6. Vehicle position and adjacent lane encroachment.

3.5.4 Centerline or Median Encroachment

Applicable to single lane roadways with an undivided or traversable median, centerline or median encroachment is defined as the vehicle tires contacting or going over the centerline or median. Centerline or median encroachment is relevant to the study of bicycle safety because roadways with different median configurations may impact driving behavior with regard to vehicle lane positioning and passing lateral distance from bicycles. Vehicle position and centerline/median encroachment were extracted from video from different angles when the vehicle was in parallel to the bicyclist. Figure 7 illustrates the encroachment considered for single lane roadways in this study. POS=0 consists of the vehicle remaining within the travel lane and not contacting the centerline or median with the vehicle's tires. POS=1 represents any centerline or median encroachment, including the vehicle's left-side tires contacting the centerline, the vehicle completely crossing over the centerline or the edge of the median into the opposite lane or median.

Modeling of centerline/median encroachment (EN) was conducted using binary and ordinal logistic regression to assess the effect of median type (UND = undivided, HM = hatched median, TWLTL = two-way left turn lane, RM = raised median), roadway geometry (LN = lane

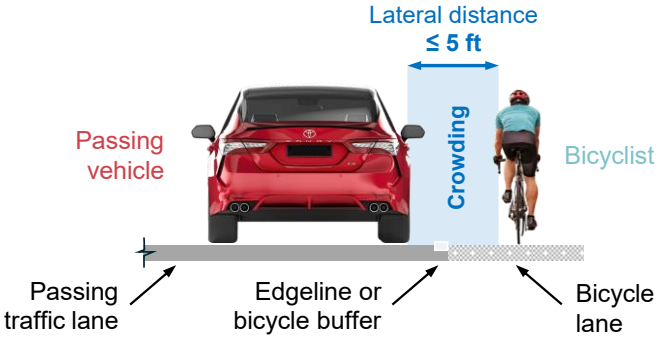
width, BF = bicycle buffer, GT = gutter width), vehicle type (passenger or large vehicle, VH), lead or follower vehicle (FOL), and opposing traffic (OPT). Response binary variables consisted of encroachment (ENC=1) and no encroachment (ENC=0). Modeling of passing lateral distance (LD) was conducted using generalized linear regression to assess the effect of the same predictor variables. The presence of opposing traffic was defined as the time headway when an opposing vehicle was 8 s or less from the bicyclist at the time when the passing vehicle was in parallel to the bicyclist. The 8 s threshold was derived based on AASHTO's Green Book passing sight distance for two lane highways (Harwood et al. 2008; AASHTO 2018). A vehicle was considered to be in a following state when the time headway with the vehicle in front was equal to or less than 5 s (NASEM 2022).



Note: Not to scale.
Figure 7. Centerline or median encroachment.

3.5.5 Crowding

Crowding is a passing event in which the lateral distance between a motor vehicle and a bicyclist is sufficiently small to impact the bicyclist's operating space, positioning, comfort, and perceived risk. Based on minimum passing distance practices (Lamb et al. 2020; NCLS 2023) and existing literature (Kay et al. 2014), passing observations with lateral distance equal to or less than 5.0 ft (1.5 m) were considered crowding events. Figure 8 illustrates crowding events.



Note: Not to scale.
Figure 8. Crowding events.

Modeling of crowding (CRW) was conducted using binary logistic regression to assess the effect of median type (UND = undivided, HM = hatched median, TWLTL = two-way left turn lane, RM = raised median), roadway geometry (LN = lane width, BF = bicycle buffer, GT = gutter width), vehicle type (passenger or large vehicle, VH), lead or follower vehicle (FOL), adjacent or opposing traffic (AT or OPT). Response binary variables consisted of crowding (CRW=1) and no crowding (CRW=0).

3.6 Regression Analysis

3.6.1 Binary Logistic Regression

Binary logistic regression is a statistical modeling approach used when the dependent variable has two possible outcomes (y = 0 and y = 1) to compare a reference condition to a specified condition. Predictor variables are evaluated to assess the likelihood that the outcome equals category y = 1. The model is specified in terms of the log-odds of the outcome as a linear function of predictors, which allows the inclusion of continuous and categorical predictor variables. These log-odds are then transformed through a logistic function to produce predicted probabilities that range between 0 and 1. Equations 1 and 2 provide the binary logistic regression specification. Each regression coefficient represents the change in the log-odds of the outcome associated with a one-unit increase in the corresponding predictor, holding all other variables constant. When exponentiated, these coefficients can be interpreted as odds ratios, which describe how the odds of the outcome change with the predictors. Results can also be provided as marginal effects (averaged across the sample), which quantify how a change in a predictor variable affects the predicted probability of the outcome. Centerline or median encroachment (EN) (only single lane Sites RR and LA) and crowding (CRW) (all sites) were modeled using binary logistic regression.

$$\eta = logit[P(y = 1)] = \beta_0 + \beta_1 \times x_1 + \cdots + \beta_n \times x_n \quad \text{(E.1)}$$

$$P(y = 1) = \frac{1}{1+e^{-\eta}} \quad \text{(E.2)}$$

Where,

η = linear predictor, log-odds of the outcome,
y = outcome variable (y = 0 or y = 1),
β_0 = intercept,
β_n = regression coefficients,
x_n = predictor variables,
$P(y = 1)$ = probability of the outcome variable y = 1.

3.6.2 Ordinal Logistic Regression

Ordinal logistic regression is a statistical modeling approach used when the dependent variable consists of ordered categories such as y = 0, 1, …, M. Ordinal logistic regression models the relationship between predictor variables and the likelihood that the outcome falls at or below a given category. The model estimates cumulative probabilities across the ordered categories. The model is specified in terms of the cumulative log-odds of the outcome up to each category as a function of the predictors. It also allows continuous and categorical predictor variables. The cumulative log-odds are then transformed through a logistic function to produce cumulative probabilities that range between 0 and 1. Equations 3 and 4 provide the ordinal logistic regression specification. Each regression coefficient represents the change in the cumulative log-odds of

being in an equal or lower category associated with a one-unit increase in the corresponding predictor variable, holding all other variables constant. Multiple thresholds (intercepts), one for each category, are used in the model to define the boundaries between adjacent outcome levels. Under the proportional odds assumption, the regression coefficients are constant across all category thresholds. Only for the multilane configuration (Site FH), vehicle position and adjacent lane encroachment were modeled using ordinal logistic regression based on all the position categories POS=0–4.

$$\eta_m = logit[P(y \leq m)] = \theta_m - (\beta_1 \times x_1 + \cdots + \beta_n \times x_n) \quad \text{(E.3)}$$

$$P(y \leq m) = \frac{1}{1+e^{-\eta_m}} \quad \text{(E.4)}$$

Where,

η_m = linear predictor, cumulative log-odds of the outcome up to category m,
y = ordinal outcome variable with ordered categories (y = 0, 1, …, M),
θ_m = threshold (intercept) for category m,
β_n = regression coefficients,
x_n = predictor variables,
$P(y \leq m)$ = cumulative probability that the outcome is in category m or lower.

3.6.3 Generalized Linear Models

Generalized Linear Models (GLM) are an extension of classical linear regression that allows modeling the relationship of predictors and a response variable that does not follow a normal distribution. GLM accommodates heteroscedasticity in which the variance of residuals across predictor variables are non-constant, allowing different error structures and complexities in the data, providing a more accurate representation of the variance. Equation 5 provides the formulation of the GLM used. In previous studies, Claros et al. (2024, 2026) found that the distribution of passing lateral distance and speed had skewed distributions and did not follow a normal distribution.

$$\mu_i = E(y_i) = e^{(\beta_0+\beta_1\times x_1+\cdots+\beta_n\times x_n)} = e^{\beta_0} \times e^{\beta_1\times x_1} \times \ldots \times e^{\beta_n\times x_n} \quad \text{(E.5)}$$

Where,

y_i = observed outcome (i.e., lateral distance or speed),
μ_i = mean or expected value of the observed outcome,
$x_1 \ldots x_n$ = predictor variables (i.e., opposing traffic, lane width, etc.),
$\beta_0 \ldots \beta_n$ = model coefficients.

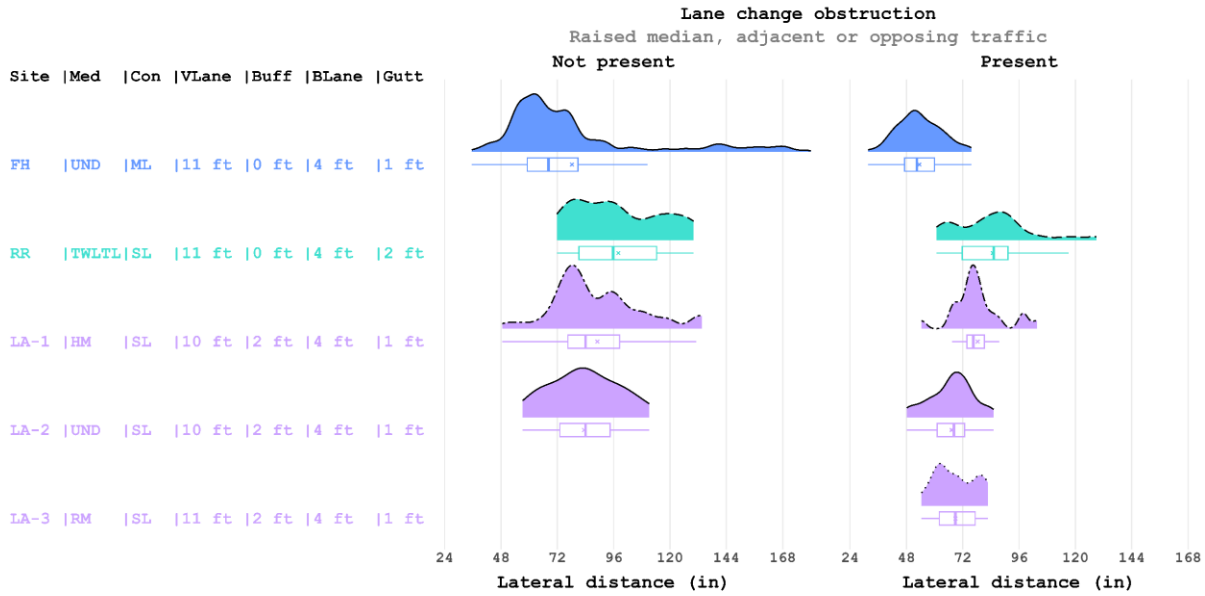
Effects in the GLM structure are multiplicative, so a one unit increase in a predictor variable x_j would have an effect on the mean of the observed outcome equal to e^{β_j}, which indicates an increasing ($e^{\beta_j} > 1$) or decreasing ($e^{\beta_j} < 1$) effect on the mean. Predictor variables' effect can also be expressed in percent change of the mean as $(e^{\beta_j} - 1) \times 100\%$. The effects of road geometry and operations in passing vehicles' lateral distance and speed were evaluated.

4. RESULTS

4.1 Lateral Distance

4.1.1 Lateral Distance Descriptive Statistics

Descriptive statistics and distribution of passing lateral distance observations were evaluated according to the number of lanes, median type, bicycle buffer, adjacent or opposing traffic. There were a total of 679 passing vehicle observations, of which 471 were with no adjacent or opposing traffic, and 208 were with adjacent or opposing traffic. Figure 9 provides lateral distance density and box plots. Table 2 provides passing lateral distance statistics.



Notes: Grouping by site and median type. Site = location, FH: Fish and Hatchery Rd, RR: Rimrock Rd, LA: Lacy Rd, and id number (none, 1–3); Med = median type, UND: undivided (solid line —), TWLTL: two-way left turn lanes (dashed line – –), HM: hatched median (dot-dash line – - –), and RM: raised median (dotted line ···); Con = configuration, ML: multilane and SL: single lane; VLane = vehicle lane width; Buff = bicycle lane buffer; BLane = bicycle lane width; Gutt= gutter width; Symbols **|** = median and **×** = mean; Units in ft = feet and in = inches. It was assumed that the physical obstruction of the raised median had a similar effect as the presence of parallel or opposing traffic, and parallel or opposing traffic not present was not applicable for Site LA-3.

Figure 9. Passing lateral distance densities and boxplots.

Obstructions that limit the traversal of passing vehicles to adjacent or opposing traffic lanes include raised medians, vehicles in adjacent lane, or vehicles in opposing traffic. According to the roadway configurations, the presence of any of these lane change obstructions significantly reduced the passing lateral distance.

The roadway configuration with two vehicular lanes and non-buffered bicycle lanes (Site FH) had the smallest mean lateral distance among all roadway configurations evaluated. For instance, with adjacent or opposing traffic present, the mean lateral distance at Site FH was 54 in (137 cm) compared to 69 in (175 cm) at Site LA-3, 67 in (170 cm) at Site LA-2, 78 in (198 cm) at Site LA-1, and 85 in (216 cm) at Site RR. The distribution of observations for Site FH, without adjacent traffic, showed a concentration of lateral distances between 36–96 in (91–244 cm) and an extended tail with lateral distances up to 180 in (457 cm). The extended tail represents observations of vehicles crossing over to or encroaching the adjacent lane. Although adjacent traffic was not present in observations at Site FH, the majority of the vehicles remained within the

lane next to the bicyclist and did not change lanes when passing the bicyclist. In contrast, when adjacent traffic was present at Site FH, the passing lateral distances were less than 78 in (198 cm).

Site RR, configuration including a TWLTL median with two lanes and non-buffered bicycle lanes, had the largest mean lateral distances with (98 in, 249 cm) or without (85 in, 216 cm) opposing traffic among all roadway configurations. Since the TWLTL median was 14.0 ft (4.3 m) wide, passing vehicles had more available space to pass the bicyclist even with the presence of opposing traffic.

Although there were no single lane road configurations without bicycle buffer to evaluate its effect on lateral distance, Sites FH and LA with lane change obstruction provided equivalent conditions for comparison. Mean lateral distance was 13–24 in (33–61 cm) less when having a bicycle buffer of 2 ft or 24 in (61 cm). The bicycle buffer seems to proportionally increase the passing lateral distance on single lane configurations.

On single lane roadways, raised medians restrict the available space for all passing maneuvers, increasing the overall probability of smaller lateral distances.

Table 2. Passing lateral distance statistics.

Site[1]	Number of lanes	Lane width (ft)		Bicycle buffer (ft)	Gutter (ft)	Median type[2]	Passing lateral distance (in) with adjacent or opposing traffic							
							Not present				Present			
		Vehicle	Bicycle				Obs.[3]	Mean	Median	St. dev.[4]	Obs.[3]	Mean	Median	St. dev.[4]
FH	4	11	4	0	1	UND	319	78	68	31	123	54	53	9
RR	2	11	4	0	2	TWLTL	31	98	96	18	23	85	85	17
LA-1	2	10	4	2	1	HM	59	89	84	19	23	78	77	11
LA-2	2	10	4	2	1	UND	36	83	84	15	39	67	68	9
LA-3	2	11	4	2	1	RM	N/A	N/A	N/A	N/A	26	69	69	9
							471				208			

Notes: [1] FH = Fish Hatchery Rd, RR = Rimrock Rd, LA = Lacy Rd; [2] UND = undivided, TWLTL = two-way left turn lane (14 ft), HM = hatched median (2–10 ft), RM = raised median (7–17 ft). N/A = not applicable, NA = not available.

Table 3. Passing speed statistics.

Site[1]	Number of lanes	Lane width (ft)		Bicycle buffer (ft)	Gutter (ft)	Median type[2]	Passing speed (mph) with adjacent or opposing traffic							
							Not present				Present			
		Vehicle	Bicycle				Obs.[3]	Mean	Median	St. dev.[4]	Obs.[3]	Mean	Median	St. dev.[4]
FH	4	11	4	0	1	UND	319	36	35	4	123	34	34	3
RR	2	11	4	0	2	TWLTL	31	36	35	3	23	35	35	4
LA-1	2	10	4	2	1	HM	59	35	34	4	23	34	33	3
LA-2	2	10	4	2	1	UND	36	34	34	4	39	33	33	4
LA-3	2	11	4	2	1	RM	N/A	N/A	N/A	N/A	26	33	34	4
							471				208			

Notes: [1] FH = Fish Hatchery Rd, RR = Rimrock Rd, LA = Lacy Rd; [2] UND = undivided, TWLTL = two-way left turn lane (14 ft), HM = hatched median (2–10 ft), RM = raised median (7–17 ft). N/A = not applicable.

4.1.2 Effects on Lateral Distance

Effects on mean passing lateral distance were modeled as a function of roadway geometric and operational variables using generalized linear regression and data from Sites LA and RR (single lane configurations). The model is presented in Equation 6, and the results are provided in Table 4. The outcome variable is mean lateral distance (LD) and predictor variables are median type (UND = undivided, HM = hatched median, TWLTL = two-way left turn lane, RM = raised median), opposing traffic (OPT), and vehicle type (VH). The base condition for median type was undivided (UND). Other predictor variables were explored but were not included in the model due to a lack of statistical significance or relevance to the response variable.

$$LD = e^{(\beta_0+\beta_1\times HM+\beta_2\times TWLT+\beta_3\times RM+\beta_4\times OPT+\beta_5\times VH)} \quad \text{(E.6)}$$

Where,

LD = mean passing lateral distance (in),
HM = single lane roadway with hatched median and buffered bicycle lane, Site LA-1 (HM = 0 not present, HM = 1 present),
$TWLTL$ = single lane roadway with two-way left turn lane median and non-buffered bicycle lane, Site RR ($TWLTL$ = 0 not present, $TWLTL$ = 1 present),
RM = single lane roadway with raised median and buffered bicycle lane, Site LA-3 (RM = 0 not present, RM = 1 present),
OPT = opposing traffic (OPT = 0 not present, OPT = 1 present),
VH = vehicle type (VH = 0 passenger vehicle, VH = 1 large vehicle).

Table 4. Passing lateral distance generalized linear regression model, Sites LA and RR.

Variable[1]	Coefficient	Estimate	St. error	p-value	Mean LD % change
Intercept	β_0	4.405	0.024	< 0.001	N/A
HM	β_1	0.106	0.028	< 0.001	11.17%
TWLTL	β_2	0.201	0.031	< 0.001	22.29%
RM	β_3	-0.001	0.041	0.990	-0.05%
OPT	β_4	-0.165	0.025	< 0.001	-15.24%
VH	β_5	-0.185	0.049	< 0.001	-16.92%

Notes: [1] The base condition for median type was UND = undivided (Site LA-2, buffered bicycle lane), HM = hatched median (Site LA-1, buffered bicycle lane), TWLTL = two-way lane turn lane median (Site RR, non-buffered bicycle lane), RM = raised median (Site LA-3, buffered bicycle lane), OPT = opposing traffic, VH = vehicle type. N/A = not applicable.

The model coefficients in Table 4 show that HM median with buffered bicycle lanes (β_1 = 0.106) and TWLTL median with non-buffered bicycle lanes (β_2 = 0.201) had statistically significant effects in increasing passing lateral distance. RM median with buffered bicycle lanes (β_3 = -0.001) did not have a statistically significant effect on passing lateral distance. Opposing traffic OPT (β_4 = -0.165) and vehicle type VH (β_5 = -0.185) had statistically significant effects in reducing passing lateral distance. Results expressed in percentage change indicate that mean passing lateral distance:

- Increased by 11% with HM median with buffered bicycle lanes.
- Increased by 22% with TWLTL median with non-buffered bicycle lanes.
- Did not change with RM median with buffered bicycle lanes.

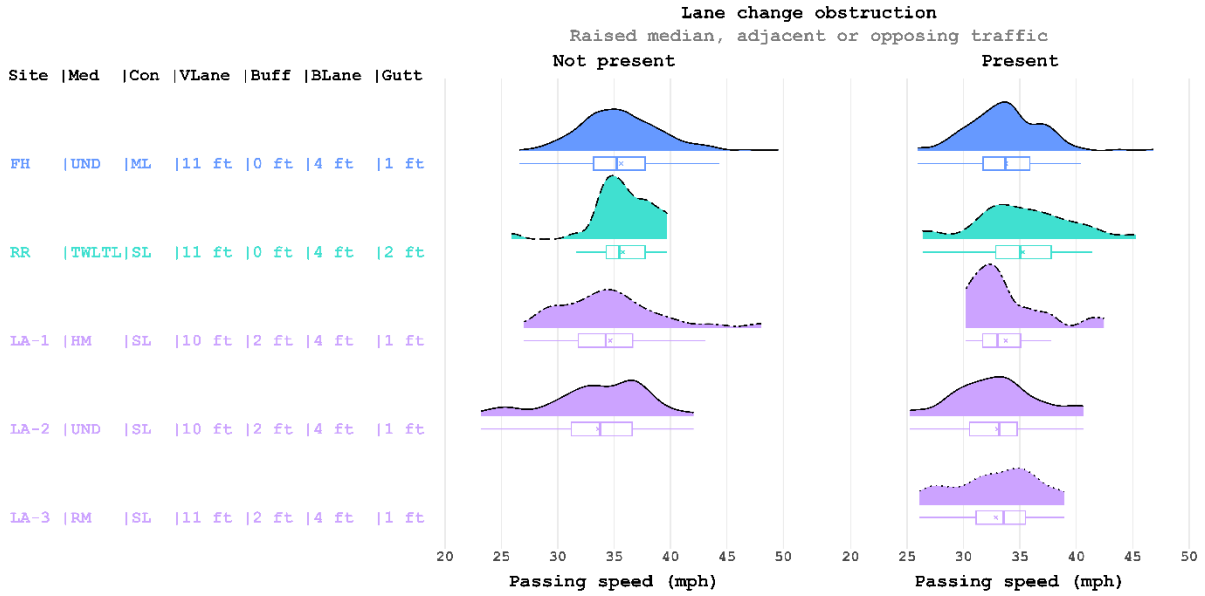
- Decreased by 15% with the presence of opposing traffic.
- Decreased by 17% with large vehicles.

4.2 Passing Speed

4.2.1 Passing Speed Descriptive Statistics

Exploratory data analysis of passing speeds was evaluated according to the number of lanes, median type, bicycle buffer, adjacent or opposing traffic. There were a total of 679 passing vehicle observations, of which 471 were with no adjacent or opposing traffic, and 208 were with adjacent or opposing traffic. Figure 10 provides passing speed density and box plots. Table 3 provides passing speed statistics.

Results showed that passing speeds were lower with a raised median, adjacent or opposing traffic. Observations at Site FH (multilane configuration), with no adjacent traffic, showed a significantly higher mean passing speed (+6.0 mph, +9.7 kph) compared to the posted speed limit, whereas at the rest of the sites (single lane with raised median or opposing traffic), mean passing speeds were close to the posted speed limit (±1.0 mph, 1.6 kph).



Notes: Grouping by site and median type. Site = location, FH: Fish and Hatchery Rd, RR: Rimrock Rd, LA: Lacy Rd, and id number (none, 1–3); Med = median type, UND: undivided (solid line —), TWLTL: two-way left turn lanes (dashed line – –), HM: hatched median (dot-dash line – - –), and RM: raised median (dotted line ···); Con = configuration, ML: multilane and SL: single lane; VLane = vehicle lane width; Buff = bicycle lane buffer; BLane = bicycle lane width; Gutt= gutter width; Symbols **I** = median and **×** = mean; Units in ft = feet and mph = miles per hour. It was assumed that the physical obstruction of the raised median had a similar effect as the presence of parallel or opposing traffic, and parallel or opposing traffic not present was not applicable for Site LA-3. The posted speed limit at Site FH was 30 mph and at Sites RR and LA was 35 mph.

Figure 10. Passing speed densities and boxplots.

4.2.2 Effects on Passing Speed

Effects on mean passing speed were also modeled as a function of roadway geometric and operational variables using generalized linear regression and data from Sites LA and RR (single lane configurations). The model is presented in Equation 7, and the results are provided in Table 5. The outcome variable is mean passing speed (VS), and the predictor variable is median type (UND = undivided, HM = hatched median, TWLTL = two-way left turn lane, RM = raised median).

The base condition for median type was undivided (UND). Other predictor variables were explored but were not included in the model due to a lack of statistical significance, relevance, or confounding effect. Given the limited sample size of single lane roadway configurations, results were corroborated with the distribution of the data, and the significance level for the model coefficients was 0.1.

$$VS = e^{(\beta_0+\beta_1\times HM+\beta_2\times TWLT+\beta_3\times RM)} \quad \text{(E.7)}$$

Where,

VS = mean passing speed (mph),
HM = single lane roadway with hatched median and buffered bicycle lane, Site LA-1 (HM = 0 not present, HM = 1 present),
$TWLTL$ = single lane roadway with two-way left turn lane median and non-buffered bicycle lane, Site RR ($TWLTL$ = 0 not present, $TWLTL$ = 1 present),
RM = single lane roadway with raised median and buffered bicycle lane, Site LA-3 (RM = 0 not present, RM = 1 present).

Table 5. Passing speed generalized linear regression model, Sites LA and RR.

Variable[1]	Coefficient	Estimate	St. error	p-value	Mean VS % change
Intercept	β_0	3.505	0.013	< 0.001	N/A
HM	β_1	0.033	0.018	0.072	3.38%
TWLTL	β_2	0.067	0.021	0.001	6.87%
RM	β_3	-0.012	0.026	0.649	-1.19%

Notes: [1] The base condition was UND = undivided (Site LA-2, buffered bicycle lane), HM = hatched median (Site LA-1, buffered bicycle lane), TWLTL = two-way lane turn lane median (Site RR, non-buffered bicycle lane), RM = raised median (Site LA-3, buffered bicycle lane). N/A = not applicable.

The model coefficients in Table 5 show that HM median with buffered bicycle lanes (β_1 = 0.033) and TWLTL median with non-buffered bicycle lane (β_2 = 0.067) had statistically significant effects in increasing passing speed. RM median with buffered bicycle lanes (β_3 = -0.012) did not have a statistically significant effect on passing speed. Results expressed in percentage change indicate that mean passing speed:

- Increased by 3% with HM median with buffered bicycle lanes.
- Increased by 7% with TWLTL median with non-buffered bicycle lanes.
- Did not change with RM median with buffered bicycle lanes.

4.3 Adjacent Lane Encroachment

Adjacent lane encroachment with the left-side tires of the vehicle (POS=1) was 50% with adjacent traffic not present and 95% with adjacent traffic present. With the broken lane line in between the vehicles' tires (POS=2), encroachment was between 31% with adjacent traffic not present and 5% with adjacent traffic present. For the rest of vehicle positions with adjacent traffic not present, the vehicle's right tire on the centerline (POS=3) and completely over the adjacent lane (POS=4), encroachments were 4% and 8%, respectively. As expected, with adjacent traffic present limiting the available space, encroachments with vehicle positions POS = 3 and 4 were not observed for that condition. Figure 11 illustrates the distribution of the extent of encroachments for Site FH (multilane configuration). The results show that although there was no adjacent traffic present and

the available space in the adjacent lane to move over, 50% of vehicles remained within the lane next to the bicyclist when passing.

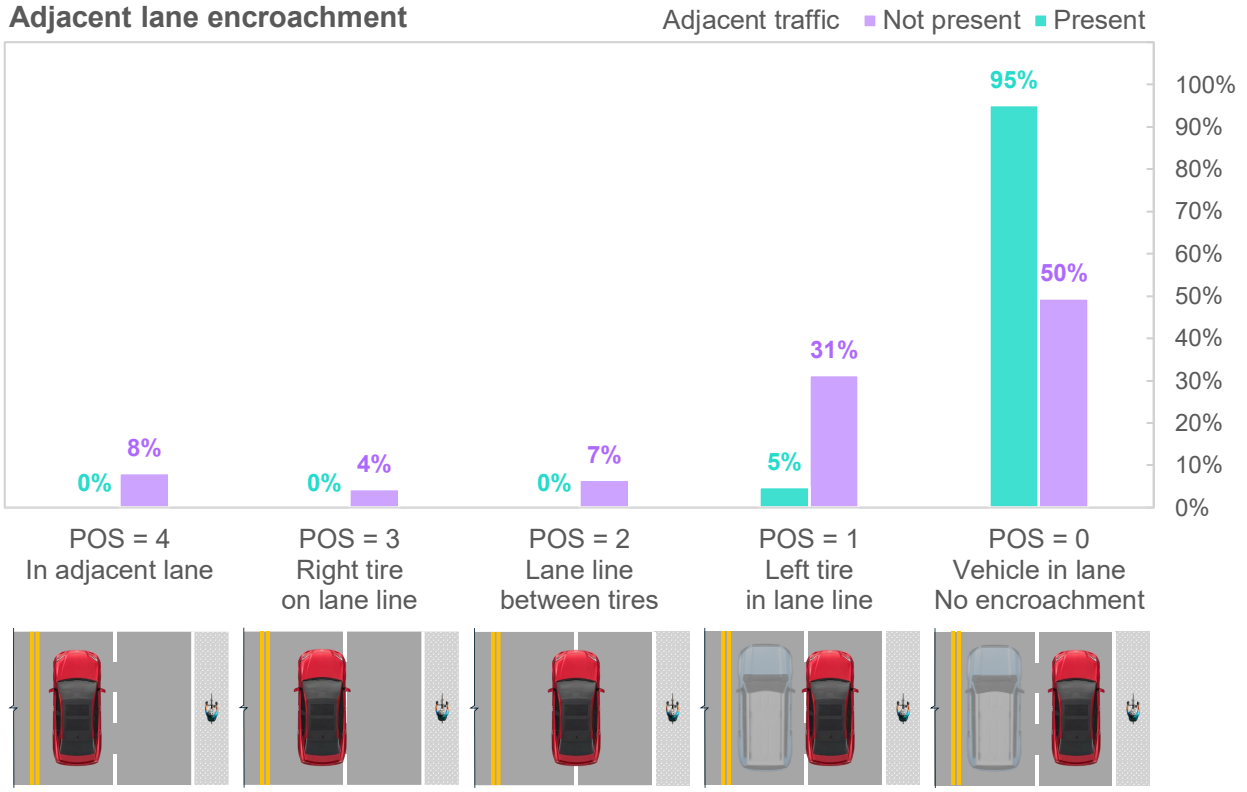


Figure 11. Distribution of adjacent lane encroachment, Site FH.

Extent of encroachment (POS) was modeled as a function of presence of adjacent traffic (AT) using ordinal logistic regression. The results are provided in Equations 8–12 and Tables 6–7. Modeling was conducted using data from Site FH, which is a multilane roadway.

$$P(POS = 0) = \frac{1}{1+e^{-[\theta_1-(\beta_1\times AT)]}} \quad \text{(E.8)}$$

$$P(POS = 1) = \frac{1}{1+e^{-[\theta_2-(\beta_1\times AT)]}} - \frac{1}{1+e^{-[\theta_1-(\beta_1\times PT)]}} \quad \text{(E.9)}$$

$$P(POS = 2) = \frac{1}{1+e^{-[\theta_3-(\beta_1\times AT)]}} - \frac{1}{1+e^{-[\theta_2-(\beta_1\times PT)]}} \quad \text{(E.10)}$$

$$P(POS = 3) = \frac{1}{1+e^{-[\theta_4-(\beta_1\times AT)]}} - \frac{1}{1+e^{-[\theta_3-(\beta_1\times PT)]}} \quad \text{(E.11)}$$

$$P(POS = 4) = 1 - \frac{1}{1+e^{-[\theta_4-(\beta_1\times AT)]}} \quad \text{(E.12)}$$

Where,

$P(POS = n)$ = probability of passing vehicle position in relation to the lane broken white line (POS = 0 vehicle in the lane, POS = 1 left tire on lane broken white line, POS = 2 lane broken white line in between tires, POS = 3 right tire on lane broken white line, and POS = 4 in adjacent lane),

AT = adjacent traffic (AT = 0 not present, AT = 1 present).

Table 6. Extent of adjacent lane encroachment at Site FH, ordinal logistic regression model.

Variables		Coefficient	Estimate	Standard error	p-value	Odds ratio (conf. interval)[3]
Intercept[1]	0|1	θ_1	-0.028	0.112	0.805	N/A
	1|2	θ_2	1.465	0.143	< 0.001	N/A
	2|3	θ_3	1.964	0.169	< 0.001	N/A
	3|4	θ_4	2.443	0.205	< 0.001	N/A
Slope[2]	AT	β_1	-3.010	0.433	< 0.001	0.05 (0.02, 0.11)

Notes: [1] Vehicle in the lane POS = 0, left tire on broken white lane line, POS = 1, lane broken white line in between tires POS = 2, right tire on lane broken white line POS = 3, in adjacent lane POS = 4; [2] AT = parallel or adjacent traffic; [3] 95% confidence interval, N/A = not applicable, intercepts are constant values and odds ratios don't apply.

Table 7. Extent of adjacent lane encroachment at Site FH, marginal effects.

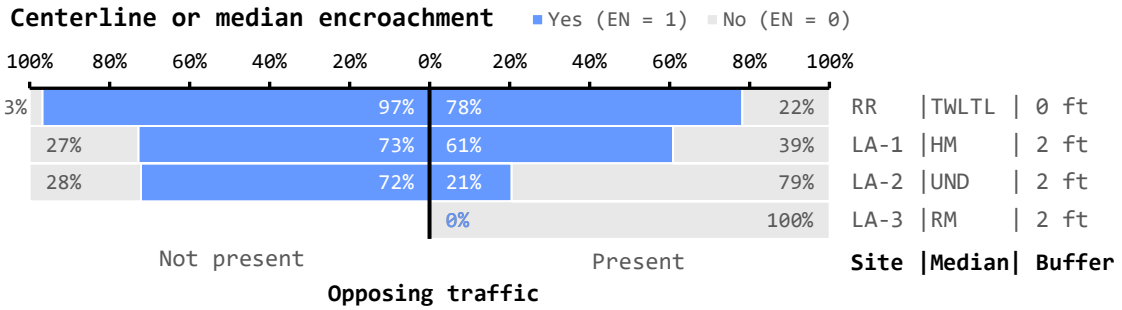
Variable[1]	POS[2]				
	0	1	2	3	4
AT	0.459	-0.282	-0.060	-0.041	-0.076

Notes: [1] AT = parallel or adjacent traffic; [2] Vehicle in the lane POS = 0, left tire on broken white lane line, POS = 1, lane broken white line in between tires POS = 2, right tire on lane broken white line POS = 3, in adjacent lane POS = 4.

The model coefficients in Table 6 show that adjacent traffic (β_1 = -3.010) had a statistically significant effect in reducing the propensity for greater extents of adjacent lane encroachment while passing a bicyclist riding in the bicycle lane. Results indicate that the odds of greater extents of adjacent lane encroachment (with positions further into the adjacent lane) decreased by 95% when adjacent traffic was present. Based on the results of average marginal effects in Table 7, the probability of vehicles remaining in the lane (POS = 0), not encroaching the adjacent lane, increased by 46% with the presence of adjacent traffic.

4.4 Centerline or Median Encroachment

Centerline and median encroachment was evaluated for single lane configurations (Sites RR and LA). Vehicles encroaching the centerline or median were significantly impacted by the presence of opposing traffic. Percentage of encroachment ranged between 72–97% with no opposing traffic, compared to 0–78% with opposing traffic. Site RR had the highest percentage of encroachment with (78%) or without (97%) opposing traffic, attributed to the wide median providing more available space for passing vehicles to move over the median when passing bicyclists. Without opposing traffic, Sites LA-1 and LA-2 (hatched and undivided median) had similar encroachment percentages of 73% and 72%, respectively. With opposing traffic present, Site LA-1 had an encroachment percentage of 61% compared to Site LA-2 of 21%. The additional space of a hatched median (2–10 ft, 0.6–3.0 m) is less restrictive for passing vehicles to move further away from bicycles when opposing traffic is present. In the case of Site LA-3, undivided median, the available space is limited to the passing lane width and bicycle buffer when opposing traffic is present, which reduces centerline encroachment. In some instances, or when the passing vehicle went over the centerline, opposing traffic would move over further away from the centerline to provide more space to vehicles passing the bicyclist. In the case of Site LA-3, the raised median restricts any encroachment to the centerline and strictly limits operations within the passing lane.



Notes: TWLTL = two-way left turn lane median, HM = hatched median, UND = undivided median, RM = raised median. It was assumed that the physical obstruction of the raised median had a similar effect as the presence opposing traffic, and opposing traffic not present was not applicable for Site LA-3.

Figure 12. Distribution of centerline or median encroachment.

Centerline or median encroachment (EN) was modeled as a function of median type (TWLTL, HM, and UND) and presence of opposing traffic (AT) using binary logistic regression. Site LA-3 was not included in the model because the site had a non-traversable raised median, so centerline encroachment was not applicable. The results are provided in Equation 13 and Table 8. Modeling was conducted using data from Sites RR and LA, which are single lane roadways. The base condition for median type was undivided (UND).

$$P(EN = 1) = \frac{1}{1+e^{-(\beta_0+\beta_1\times HM+\beta_2\times TWLT+\beta_3\times OPT)}} \quad \text{(E.13)}$$

Where,

$P(EN = 1)$ = probability of centerline encroachment (EN = 0 no encroachment, EN = 1 encroachment),

HM = single lane roadway with hatched median and buffered bicycle lane, Site LA-1 (HM = 0 not present, HM = 1 present),

$TWLTL$ = single lane roadway with two-way left turn lane median and non-buffered bicycle lanes, Site RR ($TWLTL$ = 0 not present, $TWLTL$ = 1 present),

OPT = opposing traffic (OPT = 0 not present, OPT = 1 present).

Table 8. Centerline or median encroachment logistic regression model, Sites LA and RR.

Variable[1]	Coefficient	Estimate	Standard error	p-value	Odds ratio (conf. interval)[2]	Marginal effect
Intercept	β_0	0.571	0.298	0.056	N/A	N/A
HM	β_1	0.749	0.358	0.036	2.12 (1.05, 4.29)	0.159
TWLTL	β_2	2.365	0.515	< 0.001	10.65 (4.13, 31.80)	0.397
OPT	β_3	-1.505	0.339	< 0.001	0.22 (0.11, 0.43)	-0.262

Notes: [1] The base condition was UND = undivided (Site LA-2, buffered bicycle lane), HM = hatched median (Site LA-1, buffered bicycle lane), TWLTL = two-way lane turn lane median (Site RR, non-buffered bicycle lane), OPT = opposing traffic; [2] 95% confidence interval. N/A = not applicable. Site LA-3 was not included in the model because the site had a non-traversable raised median, so centerline encroachment was not applicable.

Site LA-1 with a HM median with buffered bicycle lanes (β_1 = 0.749) had a statistically significant effect in increasing the propensity of median encroachment compared to Site LA-2 with an UND median with buffered bicycle lanes. Site RR with a TWLTL median with non-buffered bicycle lanes (β_2 = 2.365) had a statistically significant effect in increasing the propensity of median encroachment compared to Site LA-2 with an UND median with buffered bicycle lanes.

The presence of opposing traffic OPT (β_3 = -1.505) decreased the propensity of centerline or median encroachment.

The odds of median encroachment were 2 times higher with HM median and buffered bicycle lanes, and 11 times higher with TWLTL median with non-buffered bicycle lanes. The odds of centerline or median encroachment decreased by 78% with opposing traffic present. Results of average marginal effects indicate that the probability of centerline encroachment increased by 40% with TWLTL median with a non-buffered bicycle lane, increased by 16% with HM median with a buffered bicycle lane, and decreased by 26% when opposing traffic was present.

4.5 Crowding

Crowding was defined as the passing event in which the lateral distance between a motor vehicle and a bicyclist was equal to or less than 5.0 ft (1.5 m). Using binary logistic regression, crowding (CRW) was modeled according two roadway configuration (multilane and single lane) as a function of median type (TWLTL, HM, UND, and RM), vehicle type (VH), and adjacent or opposing traffic (AT or OPT). Respective to the roadway configuration, results are provided in Equations 14 and 15, and Tables 9 and 10.

4.5.1 Multilane Roadway Configuration, Site FH

$$P(CRW = 1) = \frac{1}{1+e^{-(\beta_0+\beta_1\times AT+\beta_2\times VH)}} \quad \text{(E.14)}$$

Where,

$P(CRW = 1)$ = probability of crowding (CRW = 0 no crowding, CRW = 1 crowding),
AT = adjacent traffic (AT = 0 not present, AT = 1 present),
VH = vehicle type (VH = 0 passenger vehicle, VH = 1 large vehicle).

Table 9. Crowding logistic regression model, Site FH.

Variable[1]	Coefficient	Estimate	Standard error	p-value	Odds ratio (conf. interval)[2]	Marginal effect
Intercept	β_0	-0.991	0.127	< 0.001	N/A	N/A
AT	β_1	2.144	0.247	< 0.001	8.53 (5.32, 14.05)	0.487
VH	β_2	1.077	0.689	0.118	2.94 (0.76, 12.24)	0.221

Notes: [1] AT = parallel or adjacent traffic, VH = vehicle type; [2] 95% confidence interval. N/A = not applicable.

The presence of adjacent traffic (β_1 = 2.144) had a statistically significant effect in increasing the propensity of crowding. The odds of crowding were 8 times higher with the presence of adjacent traffic. The probability of crowding increased by 49% when adjacent traffic was present. Due to the limited number of observations with large vehicles, vehicle type was not statistically significant. However, the model coefficient showed that large vehicles may increase the propensity of crowding (β_1 = 1.077, p-value = 0.118). There is strong evidence from the literature that large and/or heavy vehicles tend to crowd or pass bicycles closer than passenger vehicles (Walker 2007; Kay et al. 2014; Beck et al. 2019; Nolan et al. 2021; Claros et al. 2024, 2026; Strelow and Vollrath 2026).

4.5.2 Single Lane Roadway Configuration, Sites RR and LA

$$P(CRW = 1) = \frac{1}{1+e^{-(\beta_0+\beta_1\times HM+\beta_2\times TWLT+\beta_3\times RM+\beta_4\times OPT)}} \quad \text{(E.15)}$$

Where,

$P(CRW = 1)$ = probability of crowding (CRW = 0 no crowding, CRW = 1 crowding),
HM = single lane roadway with hatched median and buffered bicycle lane, Site LA-1 (HM = 0 not present, HM = 1 present),
$TWLTL$ = single lane roadway with two-way left turn lane median and non-buffered bicycle lanes, Site RR ($TWLTL$ = 0 not present, $TWLTL$ = 1 present),
OPT = opposing traffic (OPT = 0 not present, OPT = 1 present).

Table 10. Crowding logistic regression model, Sites LA and RR.

Variable[1]	Coefficient	Estimate	Standard error	p-value	Odds ratio (conf. interval)[2]	Marginal effect
Intercept	β_0	-2.388	0.528	< 0.001	N/A	N/A
HM	β_1	-0.977	0.625	0.118	0.38 (0.10, 1.21)	-0.081
TWLTL	β_2	-17.710	1436.892	0.990	2.03E-8 (NA, 3.31E+31)	-0.141
RM	β_3	-0.678	0.720	0.347	0.51 (0.10, 1.91)	-0.063
OPT	β_4	1.0287	0.5905	0.082	2.80 (0.91, 9.63)	0.067

Notes: [1] The base condition was UND = undivided (Site LA-2, buffered bicycle lane), HM = hatched median (Site LA-1, buffered bicycle lane), TWLTL = two-way lane turn lane median (Site RR, non-buffered bicycle lane), RM = raised median (Site LA-3, buffered bicycle lane), OPT = opposing traffic; [2] 95% confidence interval. N/A = not applicable, NA = not available.

The presence of a HM with buffered bicycle lanes, TWLTL median with non-buffered bicycle lanes, and RM median with buffered bicycle lanes did not have statistically significant effects on the propensity of crowding compared to an UND median with buffered bicycle lanes. The presence of opposing traffic (β_4 = 1.0287) increased the propensity of crowding. The odds of crowding were 3 times higher with opposing traffic present. Results of average marginal effects indicate that the probability of crowding increased by 7% when opposing traffic was present. Given the limited sample size for single lane roadway configurations, the significance level for the model coefficients was 0.1.

5. CONCLUSIONS

A bicycle naturalistic study was conducted to examine driver passing behavior and bicyclist safety on urban roads with different roadway geometric and operational configurations. Data from 679 observations of vehicles passing an instrumented bicycle were used in the analysis. Regression analysis was implemented to assess the effect of roadway geometric and operational conditions. Evaluation metrics included passing lateral distance, passing speed, adjacent lane encroachment, centerline encroachment, and crowding. The presence of adjacent or opposing traffic, large vehicles, and median type had statistically significant effects.

The presence of obstructions that limit the traversal of passing vehicles to adjacent or opposing traffic lanes (raised medians, vehicles in adjacent lane, or vehicles in opposing traffic) significantly reduced the passing lateral distance. The roadway configuration with a TWLTL median with two lanes and non-buffered bicycle lanes had the largest mean lateral distances among all roadway configurations. Since the TWLTL median was wide, passing vehicles had more available space to pass the bicyclist even with the presence of opposing traffic. The bicycle buffer seems to proportionally increase the passing lateral distance on single lane configurations. In terms of the type of passing vehicle, larger vehicles had a reduced passing lateral distance compared to passenger vehicles.

Passing speeds were lower with a raised median, adjacent or opposing traffic. The site with multilane configuration showed a significantly higher mean passing speed compared to the posted speed limit. Given the additional available space with TWLTL and hatched medians compared to undivided medians, greater passing speeds were observed.

On the multilane roadway configuration, adjacent traffic had reduced the propensity on greater extents of adjacent lane encroachment while passing a bicyclist riding in the bicycle lane. In terms of single lane configurations, the presence of opposing traffic reduced the propensity of centerline or median encroachment. TWLTL and hatched medians increased the propensity of median encroachment compared to the roadway with an undivided median.

The presence of adjacent (multilane) or opposing (single lane) traffic increased the propensity of crowding. Median type did not have a statistically significant effect on crowding at single lane configurations; however, these sites either had wider traversable medians or buffered bicycle lanes, which provided greater available space for passing vehicles. In contrast, on single lane roadways, raised medians restrict the available space for all passing maneuvers.

The findings from this study suggest that agencies should strive to install bicycle lane buffers, favor hatched traversable medians instead of undivided medians, limit the use of raised medians, follow guidance on bicycle lane width, and maintain bicycle lanes. Some of the limitations encountered in this study were that only a limited number of urban roadway configurations were evaluated, only one bicyclist rode the instrumented bicycle, and a limited number of observations were available for single lane configurations. Future efforts may consider collecting data in additional states, different traffic volumes and speed limits, roadside parking, and roadway configurations and available spaces with different combinations of median, vehicle lane, buffer, and bicycle lane widths.

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APPENDIX: FINAL DOCUMENTATION OF OUTPUTS, OUTCOMES, AND IMPACTS

Performance indicator Part I

Two (2) transportation-related courses were offered during the study period by the PI associated with the research project. These courses include CEE 370 (Transportation Engineering), CEE 572 (Transportation Operations), and CEE 679 (AI and Data Science in Transportation).

Performance indicator Part II

Research Performance Indicator

- Two (2) journal articles have been prepared and are under review:
  - Vehicle-Bicycle Interactions on Rural Two-Lane Roadways: Cross-Section and Available Space, Journal of Safety Research, Elsevier.
  - Vehicle-Bicycle Interactions on Urban Arterials with Bicycle Lanes, Transportation Research Record journal, Sage.
- Three (3) conference presentations were made at:
  - 2026 ASCE International Conference on Transportation and Development (ICTD), Detroit, MI.
  - 2026 ITE Wisconsin Traffic Engineering Workshop and Transportation Planning Program, Pewaukee, WI.
  - 2025 ATSIP Traffic Records Forum, Boston, MA.

Leadership Development Performance Indicators

This research project generated two (2) academic engagements and one (1) industry engagement. The PIs held positions in seven (7) national and international organizations addressing issues related to the scope of this research, including Transportation Research Board (TRB) Transportation Operations and Management Section, TRB AKL11 Performance-based Geometric Design Committee, International Advisory Committee for International Symposium on Traffic and Transportation Theory, AAA Foundation for Traffic Safety's Safe Mobility Conference, ASCE Connected and Autonomous Vehicle Impacts Committee, IEEE Emerging Transportation Technology Testing Technical Committee, and International Symposium on Navigating the Future of Traffic Management. The PIs also held editorial positions in four (4) international journals: ASCE Journal of Transportation Engineering, Part A: Systems, Accident Analysis and Prevention, Journal of Traffic and Transportation Engineering, and International Journal of Sustainable Transportation. The ASCE Transportation and Development Institute awarded Dr. David Noyce the 2026 James Laurie Prize for contributions to the advancement of transportation engineering.

Education and Workforce Development Performance Indicators

The research outcomes, including the developed methodologies, will be incorporated into course content for CEE 370 (Transportation Engineering) and CEE 572 (Transportation Operations) at the University of Wisconsin-Madison. The research will help enlarge the pool of people trained to develop knowledge and utilize at least a part of the technologies developed in this research, and to put them to use when they enter the workforce.

Output(s)

Journal Articles

- Claros, B, Chitturi, M, Bill, A, and Noyce, D. A. (under review). Vehicle-bicycle interactions on rural two-lane roadways: cross-section and available space. Accident Analysis and Prevention.
- Claros, B, Chitturi, M, Bill, A, and Noyce, D. A. (in progress). Impact of roadway geometric configuration in vehicle-bicycle interactions in urban arterials. Transportation Research Record.

Outcome(s)

The outcomes of this project contribute to the advancement of understanding of the safety of bicyclists in urban arterials. By conducting a naturalistic study, the study identified roadway geometric and operational configurations that contribute to improve safety conditions for bicyclists. Findings can be used to develop design guidance and contribute to the implementation of bicycle-friendly designs. In addition, this project has contributed to graduate-level research training in bicycle safety, supporting workforce development in emerging roadway design practices.

Impacts (s)

The application and dissemination of the project's outputs are anticipated to catalyze significant positive impacts on the transportation system safety. Laying the foundation for understanding and quantifying the vehicle-bicycle interactions will enable the development of safer design practices that would result in greater safety benefits for bicyclists. Through our research dissemination and education, this research will equip engineers, researchers, and professionals with the knowledge and skills to continue advancing the field of transportation safety and development. This will ensure a sustained impact on the transportation system's safety, reliability, and efficiency for vulnerable roadway users such as bicyclists.