Using Simulation to Assess and Reduce Conflicts between Drivers and Bicyclists

SAFETY RESEARCH USING SIMULATION

UNIVERSITY TRANSPORTATION CENTER

Jodie M. Plumert, PhD

Professor

Psychological and Brain Sciences

University of Iowa

Joseph K. Kearney, PhD

Professor

Computer Science

University of Iowa

Using Simulation to Assess and Reduce Conflicts between Drivers and Bicyclists

Jodie M. Plumert, BA, PhD
Professor
Psychological and Brain Sciences
University of Iowa
https://orcid.org/0000-0002-2150-7922

Elizabeth E. O'Neal, PhD
Postdoc
Psychological and Brain Sciences
University of Iowa
https://orcid.org/0000-0002-3934-4009

Joseph K. Kearney, BA, MA, MS, PhD
Professor
Computer Science
University of Iowa
https://orcid.org/0000-0002-0443-8152

Lakshmi Devi Subramanian, BS
PhD Student
Computer Science
University of Iowa
https://orcid.org/0000-0001-5066-011X

A Report on Research Sponsored by

SAFER-SIM University Transportation Center

Federal Grant No: 69A3551747131

April 2020

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

Table of Contents

List of Figures

List of Tables

Abstract

This paper presents an experiment conducted in a large-screen bicycling simulator to assess the impact of protected intersections on bicycle-vehicle conflicts by examining how bicyclists respond to vehicles making right-hook turns at protected vs. unprotected intersections. Participants were divided into four groups that differed by the road infrastructure (separated bike lane and protected intersections vs. conventional bike lane and unprotected intersections) and the presence (treatment) vs. absence (control) of vehicles making right-hook turns. Turning vehicles were timed to arrive at the conflict point 1 s or 1.5 s before the rider. The results show significant differences in the margin of safety between riders and turning vehicles at the conflict point where their paths cross in protected vs. unprotected intersections. The discussion focuses on the factors that underlie this difference, including the geometry of the rider's path and the site lines as riders approach the conflict point in protected vs. unprotected intersections.

1 Introduction

Separated bicycle lanes, or cycle tracks, are gaining popularity as a means to promote bicycling safety. Despite the documented benefits of separated bike lanes, including fewer crashes along protected segments and increased ridership, there remain concerns about how bicycles and vehicles interact when their paths cross at an intersection [1,2]. The fear is that following a period of separation, drivers are less likely to anticipate and scan for the presence of bicycles [3-6].

This is particularly problematic in cases where the bicyclist is continuing straight across the intersection and the driver is making a right-hand turn at the intersection. Such “right-hook crashes” pose a significant hazard for bicyclists. When cars and bicyclists are traveling in the same direction, bicyclists often come up quickly from behind and drivers often fail to notice them until it is too late. Even when bike lanes exist, the driver may begin to turn before noticing the bicyclist. Protected bike lanes are designed to reduce such conflicts by increasing the distance between the bicyclist and the vehicle at the point the driver begins to turn (see Figure 1.1). The greater distance between the driver and bicyclist is designed to (1) create visual angles that make it easier for the driver and rider to see each other, and (2) give the driver and rider more time to react before a collision.

Figure 1.1 - A rider approaching a protected intersection in the bicycling simulator.

Previous research has focused on how protected intersections influence driver behavior through field studies [7] or through experiments conducted in a driving simulator [8,9]. Deliali et al. [8] looked at how the design of protected intersections influences the speed and attentiveness of drivers in a driving simulator study. They found that larger corner islands and bigger curb extensions (which meant the vehicles had a larger turning radius) led to reduced turning speeds. Warner et al. [9] studied the effect of protected intersections on conflicts between bicyclists and drivers making right-hook turns. Results indicated that protected intersections can reduce the frequency and severity of collisions between drivers and bicyclists as compared to the case where no intersection treatments are used. In a field study, Madsen and Lahrmann [7] found that protected intersections with protected lanes were most effective in reducing conflicts between drivers and bicyclists when compared to other designs that merge bicyclists and vehicles upstream of the intersection.

Studies of how road infrastructure influences bicycling behavior have examined level of service and rider perception of safety or desirability [3]. To the best of our knowledge, there are no publications describing controlled studies that investigated the influence of protected intersections on rider behavior.

The goal of this study was to systematically test whether protected bike intersections reduce the likelihood of bicycle-vehicle conflicts involving right-hook turns by examining how bicyclists respond to cars making right-hook turns at protected vs. non-protected intersections.

2 Methods

2.1 Participants

Participants were 75 undergraduate students enrolled in an elementary psychology class at the University of Iowa. Participants were randomly assigned to either the protected intersection control condition (N = 16; 6 female; mean age = 19.10 years), protected intersection treatment condition (N = 20; 7 female; mean age = 19.00 years), unprotected intersection control condition (N = 18; 6 female; mean age = 19.38 years), or unprotected intersection treatment condition (N = 21; 9 female; mean age = 18.90). Participants received course credit for their participation. An additional 23 participants enrolled in the study but were not included in the analyses for the following reasons: symptoms of simulator sickness (N = 12; Protected – Treatment = 4, Protected – Control = 1, Unprotected – Treatment = 3, Unprotected – Control = 4), simulator malfunction during the experiment (N = 4), an inability to control the bicycle (N = 4), and issues with data recording (N = 3).

2.2 Bicycling Simulator

Our virtual environment consists of three screens placed at right angles relative to one another, forming a three-walled room (4.33 x 3.06 x 2.44 m). Three DPI MVision 400 Cine 3D projectors rear-project high-resolution, textured graphics in stereo onto the screens. An identical projector front-projects high-resolution stereo images onto the floor (4.33×3.06 m). Stereo sound is used to generate spatialized traffic sounds. Participants wear stereo shutter glasses. An OptiTrack motion capture system is used to determine the position and orientation of the participant's head based on the position of reflective markers on a helmet worn by the participant. A bicycle mounted on a stationary frame is positioned in the middle of the screens. A motor is connected to the rear wheel of the bicycle through a chain and gearing hub. A 26 lb, 12.5 in diameter flywheel is mounted between the motor and the gear in order to provide rotational inertia that is equivalent to the mechanical inertia of a rider. The inertia can be adjusted through gearing to simulate the mass of the rider. The bike is instrumented to sense steering angle and the speed of the rear wheel, which are combined with head position to render in real time the images corresponding to the rider's movement through the virtual environment. The virtual environment software is based on the Unity3D gaming platform. Unity3D manages the main simulation loop, runs an in-house scenario code that generates the traffic, and renders images that are displayed by the projectors. The computer software records the position (x and y coordinates) of the rider and the traffic in real time. This information is used to automatically calculate variables such as riding speed and steering deviation for later analysis.

2.3 Design

We used a mixed between- and within-subjects design. We manipulated between subjects whether bicyclists always rode through protected or unprotected intersections and whether the vehicles only drove straight (control) or also made right turns at intersections (treatment). This resulted in four between-subjects conditions: (1) unprotected intersection control condition, (2) unprotected intersection treatment condition, (3) protected intersection control condition, and (4) protected intersection treatment condition. For both control conditions, all vehicles drove straight; for both treatment conditions, half of the vehicles turned right just before the rider was expected to arrive at the intersection. We also manipulated within subjects the time at which vehicles arrived at the intersection relative to the predicted time of arrival of the bicyclist.

2.4 Scenario

The experiment compared two road infrastructure designs for urban bikeways. One was a conventional on-road bicycle lane separated from traffic by a solid white line (see Figure 2.1(b)). The line separating bicycle from vehicle traffic ends just before the intersection where vehicle and bicycle traffic mix.

(a)

(b)

Figure 2.1 - Screenshots of the two road designs used in the experiment: (a) separated bicycle lane with protected intersection, (b) conventional on-road lane with unprotected intersection.

The second design was based on the so-called Dutch Intersection commonly used in the Netherlands (Figure 2.1(a)) with a bicycle lane separated from vehicular traffic along each block. The protected intersection includes a corner safety island separating vehicular and bicycle traffic. The bicycle crossing lane is set back from the intersection to create better views of a crossing bicyclist for the turning vehicle and a better view of traffic exiting the intersection for the bicyclist. In addition, the queueing area for bicyclists is pushed ahead of the queueing area for vehicles. As a consequence, right turning vehicles queued at a traffic light can better see bicyclists queued to cross their path than in conventional designs. Both designs included two opposing vehicular lanes separated by a turn lane [10,11].

In each scenario, the bicyclist crossed 24 intersections of the same infrastructure design. The traffic light was set to green in the direction of the bicyclist's travel so that neither the cyclist nor the vehicles traveling along the central road ever stopped. There was no traffic on the cross roads. Vehicles on the central road traveled at a constant speed of 25 mph.

A single vehicle overtook the rider as they approached each intersection in all conditions. In the control conditions, the vehicle drove straight through the intersection and continued down the central road. In the treatment conditions, half of the cars drove straight through the intersection and the other half turned right in front of the rider (randomly ordered). Turning vehicles were placed at a position behind the rider such that they would reach the conflict point where the path of the vehicle and bicyclist intersected either 1 s or 1.5 s before the expected time of arrival of the bicyclist based on the rider's speed at the middle of the preceding block. Non-turning cars, in both the control and treatment conditions, were placed at a position behind the rider such that they would arrive at the conflict point (had the car turned) either 1.34 s or 1.84 s before the expected time of arrival of the bicyclist based on the rider's speed at the middle of the preceding block. Vehicles were created when the bicyclist crossed the mid-point on a block (the trigger point) and placed on the road at a distance from the intersection such that they would arrive at the intersection at the desired time relative to the rider based on an assumption that the bicyclist rode at a constant speed. If the rider slowed down or sped up after the trigger point, this time interval would grow or shrink. Figure 2.1 shows a view of a car turning before the bicyclist on a protected intersection. Single vehicles traveling in the opposing direction to the bicyclist were randomly generated and never turned.

2.5 Task and Procedure

After providing informed consent, participants were taken to the bicycling simulator. Seat height adjustments were made for each participant, and gearing to the flywheel was adjusted based on participant's weight. Participants were then fitted with the tracking helmet and the stereo shutter glasses. During the familiarization phase, participants were given a brief introduction to the virtual world and an opportunity to learn how to stop, steer, and pedal the bike before testing began. During the test phase, the task for the bicyclist was to ride straight along a bike path, crossing 24 intersections where cars may or may not be making right-hook turns. Bicyclists were instructed to avoid being "hit" by cars when crossing intersections. The session took approximately 30 minutes.

We recorded the positions of the bicyclist and vehicles throughout the entire ride. This information was used to calculate the following measures:

- **Margin of safety at conflict point:** Distance of the bicyclist from the car when a turning car reached the conflict point (where their paths crossed in the intersection) in the two treatment conditions.
- **Bicyclist speed at conflict point:** Speed of the bicyclist when the turning car reached the conflict point.

- **Separation at intersection entry:** Distance of the bicyclist from the overtaking car when the car entered the intersection for all conditions.
- **Bicyclist speed at intersection entry**: Speed of the bicyclist when the overtaking car entered the intersection.
- **Speed trajectory:** The average speed of the rider in six 10 m segments from the trigger point to the beginning of the subsequent intersection. The trigger point was placed 50 m from the beginning of the next intersection. Thus, the sixth segment starts at the beginning of the intersection and continues for 10 m into the intersection.
- **Maximum deceleration:** The maximum deceleration over their trajectory as a rider approached an intersection. This was computed as the difference between the rider speed in the segment with the slowest average speed and the rider speed at the trigger point.

3 Results

Mixed-effects linear regression was used to analyze the distance and speed measures. Models included fixed effects of condition and car arrival time, as well as a random intercept of subject. Margin of safety analyses included only trials in which cars turned right at the intersection. Conversely, intersection entry analyses included only trials in which cars continued straight through the intersection. Because the separation between the car and rider for protected and unprotected intersections was significantly different based on the geometry of the intersection types (protected vs. unprotected), comparisons of control and treatment conditions were conducted separately for each intersection type.

Mixed-effects linear regression models were also used to predict maximum deceleration. Analyses first separately compared the two treatment conditions and the two control conditions. Models included fixed effects of condition and car path (turn vs. straight), as well as a random intercept of subject. Analysis of differences between the treatment and control conditions were examined separately for protected and unprotected conditions. These models each included a fixed effect of condition and a random intercept of subject.

3.1 Conflict Point Analysis for Turning Cars

3.1.1 Margin of safety at conflict point

The mixed-effects analysis revealed a main effect of intersection type, $t(71.84) = 4.00$, $p < .001$. As shown in Figure 3.1, riding through protected intersections was predictive of a 2.66 m increase in distance between the rider and car at the conflict point as compared to riding through unprotected intersections. There was also a main effect of car arrival time, $t(431.4) = -4.93$, $p < .001$, such that late-arriving cars predicted a 2.40 m decrease in distance between the rider and the car at the conflict point compared to early-arriving cars.

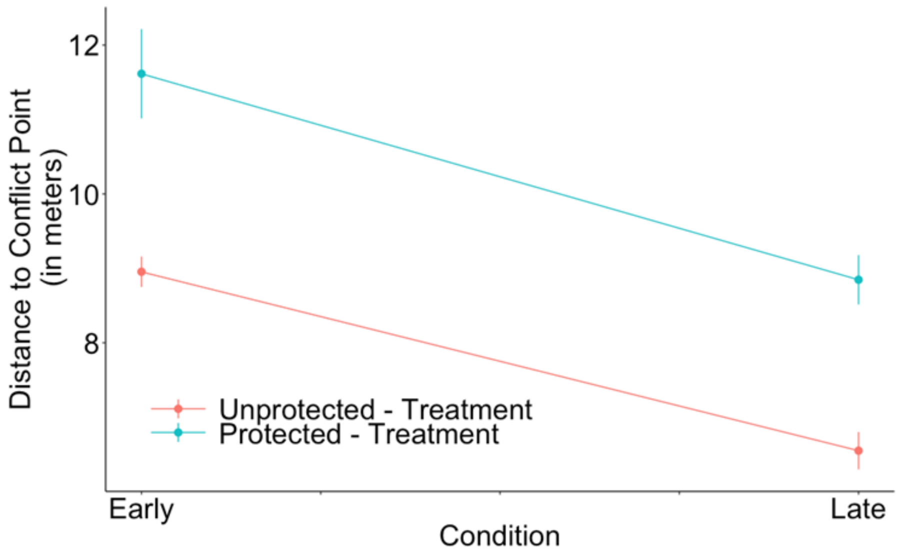

Figure 3.1 - Distance between the rider and the car at the conflict point as a function of condition and car arrival time.

3.1.2 Bicyclist speed at conflict point

There was a main effect of car arrival time for bicyclist speed at the conflict point, $t (430.14) = -2.09$, $p < .04$, such that late-arriving cars were associated with a .20 meter per second (m/s) reduction in bike speed compared to early-arriving cars (Figure 3.2). This indicates that riders slowed down more when cars arrived at the intersection later than when they arrived earlier.

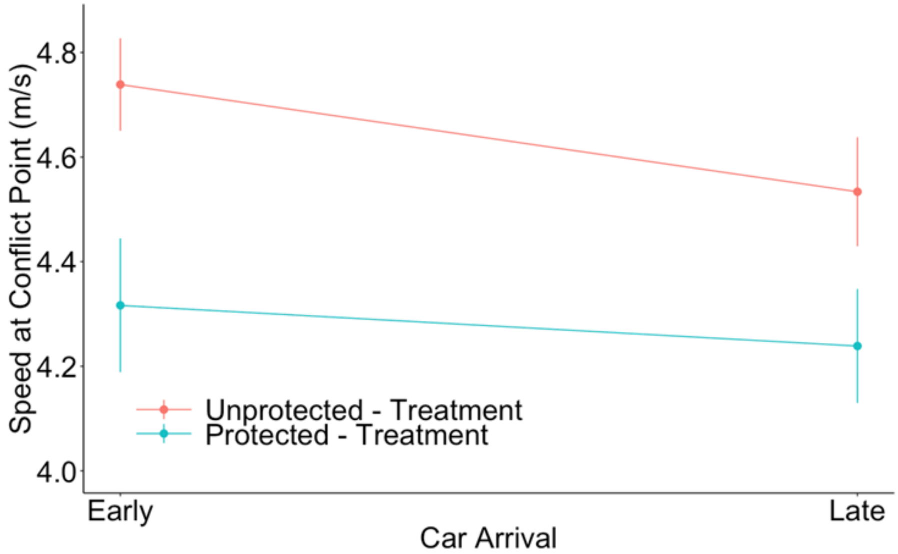

Figure 3.2 - Rider speed at the conflict point as a function of condition and car arrival time.

3.2 Car Intersection Entry Analysis for Straight-Going Cars

3.2.1 Protected intersections

***Separation at car intersection entry*.** There was a main effect of condition for separation between the car and bicyclist when straight-going cars entered the intersection, t (47.99) = 2.19, p = .03. As shown in Figure 3.3, being in the protected intersection treatment condition predicted a 1.62 m increase in distance between the rider and the car at intersection entry compared to being in the protected intersection control condition.

There was also a main effect of car arrival time for separation between the rider and car when straight-going cars entered the intersection, t (553.53) = -7.81, $p < .001$, such that late-arriving cars were associated with a 2.31 m reduction in distance compared to early-arriving cars. Again, riders slowed down more when cars arrived at the intersection later than when they arrived earlier.

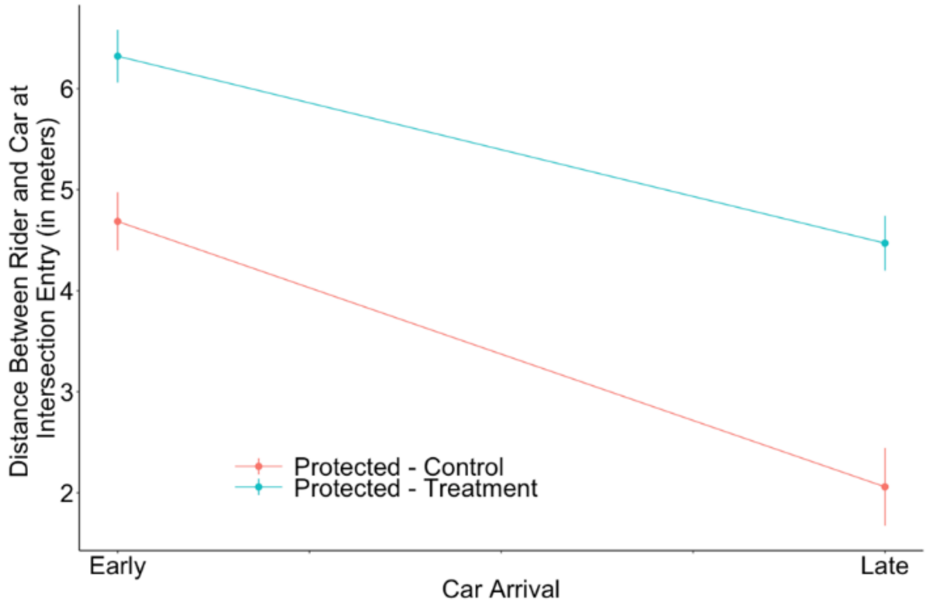

Figure 3.3 - Distance between the rider and car when the car entered the intersection for straight-going cars in the protected intersection conditions.

Speed at car intersection entry. There was no difference in bicyclist speed at car intersection entry when comparing straight-going cars in the protected control and treatment conditions, t (34.92) = 1.52, ns, or when comparing early vs. late-arriving cars, t (551.96) = -1.46, ns (Figure 3.4).

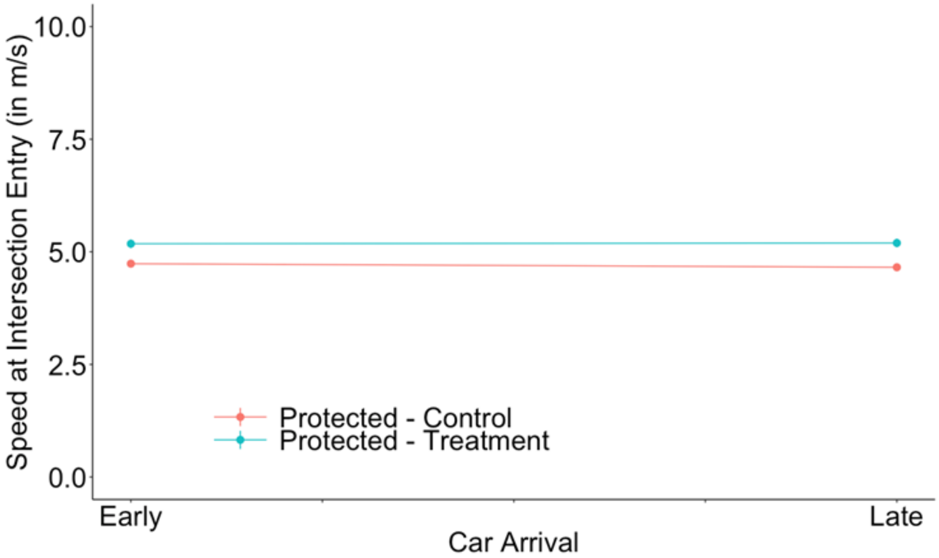

Figure 3.4 – Rider speed at car intersection entry for protected intersection conditions.

3.2.2 Unprotected intersections

Separation at car intersection entry. There was a main effect of car arrival time for distance between the rider and the car at intersection entry when straight-going cars entered the intersection, $t(553.53) = -10.92$, $p < .001$. As shown in Figure 3.5, early-arriving cars were associated with a 2.75 m increase in separation between the rider and car compared to late-arriving cars.

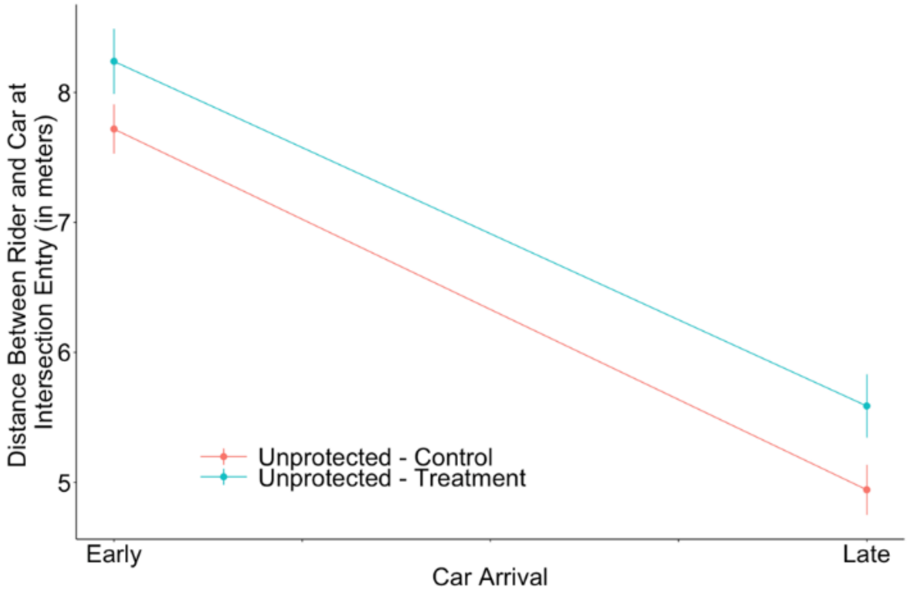

Figure 3.5 - Distance between the rider and car when the car entered the intersection for straight-going cars in the unprotected intersection conditions.

Speed at intersection entry. There was no difference in bicyclist speed at car intersection entry when comparing straight-going cars in the unprotected control and treatment conditions, t (38.32) = -.57, ns, or when comparing responses to early and late-arriving cars, t (588.91) = -.79, ns (Figure 3.6).

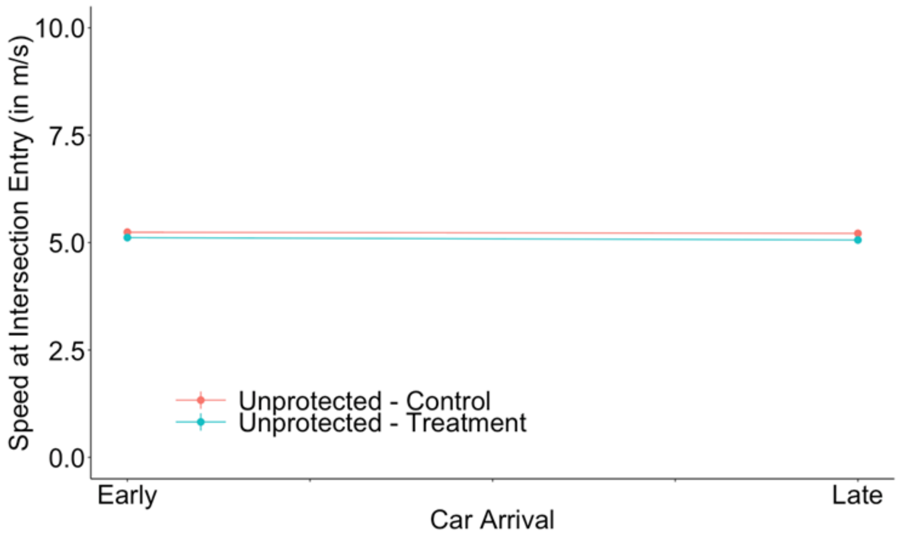

Figure 3.6 - Rider speed at car intersection entry for the unprotected intersection conditions.

4 Discussion

The results reveal three important aspects of rider performance:

1. There was a greater distance between riders and cars making right-hook turns when cars reached the conflict point for participants in the protected intersection group than for those in the unprotected intersection group. This gave riders in the protected intersection condition a greater margin of safety for the most dangerous kind of conflict between cars and bicyclists – right-hook turns.
2. The average speed of participants was lower for turning vehicles that arrived late to the conflict point than for those that arrived early. These late-arriving vehicles presented a greater threat of a collision and required a more immediate response. This shows that riders were sensitive to the specific dynamics of turning cars and responded to the immediate situation.
3. The separation between riders and straight-going cars when the cars entered the intersection was greater for riders in the treatment than in the control conditions. Recall that some cars turned and some went straight at intersections in the

treatment conditions, whereas cars only went straight at intersections in the control conditions. This demonstrates that the experience of near misses with turning cars influenced participants to ride more cautiously throughout their rides.

Why did riders have a greater margin of safety in the protected vs. unprotected conditions? Recall that vehicles were created when the rider passed a trigger point at the mid-point of the block preceding the intersection. Vehicles were placed on the road so that they would arrive at the conflict point either 1 or 1.5 s before the projected time of arrival of the bicyclist at the conflict point based on an assumption of constant riding speed. Since the vehicles always traveled at a constant speed, it must be the case that riders slowed their motion more in the protected vs. unprotected conditions on their approach to the intersection relative to their speed at mid-block.

Figure 4.1 shows the average speed of the bicyclist at the trigger point and over six consecutive 10 m segments as they rode from the trigger point (midway along a block) to the next intersection by condition. Participants reduced their speed as they approached the intersection in all conditions, reaching their lowest speed in the 10 m before entering the intersection. As expected, participants in the protected intersection treatment condition showed a greater dip in speed than did those in other conditions.

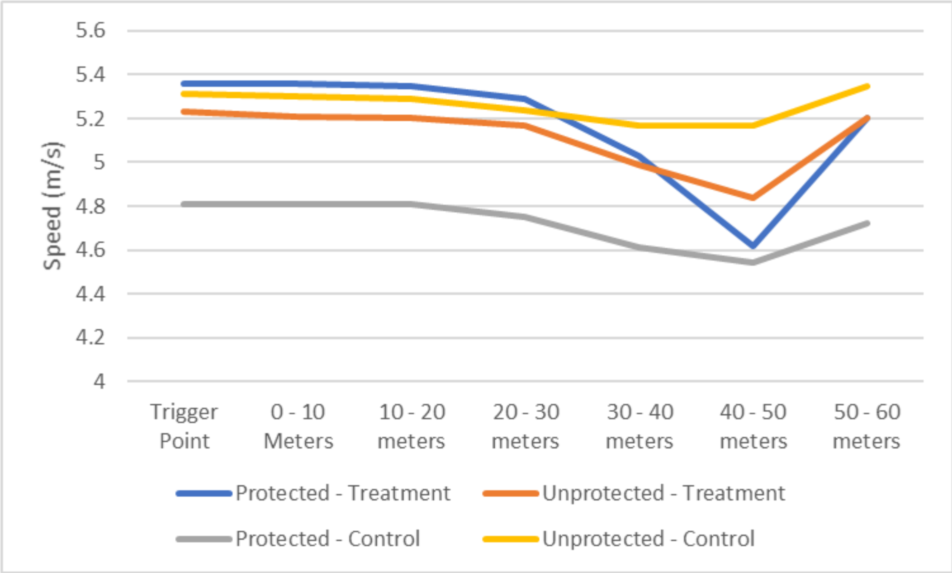

Figure 4.1 - Rider speed on approach to the next intersection. The graphs begin at the trigger point and continue for six 10 m segments ending 10 m into the intersection.

4.1 Maximum Deceleration

To analyze how riders adjusted their speed, we examined the maximum deceleration over their trajectory as they approached an intersection. This was computed as the difference between the speed in the bin with the slowest average speed and the speed at the trigger point. Table 4.1 shows the average and standard deviation of the maximum deceleration for each condition.

Table 4.1 - Average and standard deviation of maximum deceleration on approach to the intersection by condition.

Condition	Average Maximum Deceleration
Protected Intersection - Treatment	.74 (.74)
Unprotected Intersection - Treatment	.36 (.65)
Protected Intersection - Control	.27 (.43)
Unprotected Intersection - Control	.14 (.42)

4.1.1 Treatment conditions

When comparing maximum deceleration differences between the two treatment conditions, analysis indicated a significant main effect of condition, $t(46.95) = 2.47$, $p = .02$, with the protected treatment condition predicting a .32 m/s2 maximum deceleration compared to the unprotected treatment condition. This is consistent with the analysis of the distance at conflict point and explains how riders in the protected intersection treatment condition created a larger margin of safety at the conflict point by slowing as they approached the intersection.

4.1.2 Control conditions

How did the structure of the road influence deceleration in the control conditions? Because they experienced no turning cars, the control conditions show the pure effect of road geometry on riding speed. Here too, riders in the protected control condition slowed down more than riders in the unprotected control condition. Models predicting maximum deceleration between the control conditions determined that the protected control condition was predictive of a .13 m/s2 maximum deceleration as compared to the unprotected control condition, $t(46.95) = 2.14$, $p = .04$.

Together, these results indicate that deceleration can be attributed to the geometry of the protected intersection independent of the experience of encountering turning cars.

Lastly, we compare the treatment vs. control groups with respect to maximum deceleration at protected and unprotected intersections. This allows us to determine how the experience of encountering turning cars influenced maximum deceleration.

4.1.3 Protected intersections

The mixed-effects regression model revealed a main effect of condition, $t(34.09) = 3.63$, $p = .001$, indicating that the protected treatment condition was associated with a .47 m/s2 maximum deceleration compared to those in the protected control group.

4.1.4 Unprotected intersections

The mixed-effects regression model again showed that condition, t (37.15) = 2.96, p = .01, predicted maximum deceleration such that those in the unprotected treatment group were associated with a .22 m/s2 maximum deceleration compared to those in the unprotected control condition.

The difference between the treatment and control groups was that riders experienced vehicles making right-hook turns in front of them as they crossed the intersection in the treatment groups but not in the control groups. This experience led to greater deceleration as riders in the treatment conditions approached the intersection – a sign that they were more cautious in their road crossing.

To see how participants adjusted to the first experience of having a car turn in front of them, we also compared average maximum deceleration on the first trial in which a rider experienced a turning car to the average maximum deceleration on the last trial in which a car turned. There was a significant difference between the first and last turning trials for the two treatment conditions, t (39.05) = 3.03, p < .01, such that the last trial in which a car turned was associated with a .98 decrease in speed compared to the first trial in which a car turned. This shows that participants adjusted their speed trajectory once they experienced a turning car. However, this did not vary significantly by condition, *t* (75.78) = 2.62, p = .01.

Given that riders in the two treatment conditions where they experienced turning cars decelerated more than riders in the two control conditions where they did not experience turning cars, the question arises about whether riders in the treatment conditions slowed more for cars that turned than they did for cars that did not turn. One of the professed advantages of the protected intersection design is that by displacing the path of the rider from the intersection, riders can better see turning vehicles that will cross their path and adjust their behavior to avoid potential collisions. If this is true, we might expect to see riders responding differently to turning vs. straight-going vehicles and to see a difference in how riders respond to turning vs. non-turning cars in the protected vs. unprotected intersection conditions.

Table 4.2 displays the average maximum deceleration of the bicyclist in response to turning vs. straight-going cars in the two treatment conditions. Analyses indicated that car path (turn vs. straight) significantly predicted maximum rider deceleration for those in the protected treatment condition such that turning cars were associated with a .13 m/s2 max deceleration compared to straight-going cars, t (440.12) = 2.42, p = .02. Conversely, car turn type did not predict maximum rider deceleration for those in the unprotected treatment condition. Thus, riders in the protected intersection condition responded differently to turning cars than to cars that went straight, slowing more for turning cars than for straight-going cars. Riders in the unprotected intersection condition did not demonstrate a differential response to turning vs. straight-going cars.

Table 4.2 - Average maximum deceleration (m/s2) on approach to the intersection for turning vs. straight-going cars.

Condition	Straight	Turning
Protected Intersection	.67	.80
Unprotected Intersection	.35	.37

Why did riders reduce their speed more in the unprotected condition than in the protected condition? It may be that the greater visibility afforded by the protected intersection gave riders a better view of right-turning vehicles and they responded by reducing their speed. The results show that those in the protected intersection treatment group slowed more for turning cars than for straight-going cars and that riders in the unprotected intersection did not. Another factor that may have influenced rider speed is the geometry of the path that riders followed in the protected and unprotected conditions. In the unprotected condition, the path paralleled the road and, hence, was always straight. In the protected condition, the path curved as the rider entered and exited the intersection. Riders may have slowed to better negotiate the curve on entry to and exit from the intersection. The swerving necessary to negotiate each intersection may have caused some mild simulator sickness, which might have been reduced by taking the turns more slowly. The results show that the riders in the protected intersection control group slowed more than those in the unprotected intersection control group. Since the control groups did not encounter turning vehicles, this result may be related to the geometry of the rider's path. Likely, both factors influenced the degree of slowing in the treatment conditions: the greater amount of slowing in the treatment conditions reflects the influence of experiencing near misses at intersections; the amount of slowing in the control conditions reflects the baseline slowing due to the infrastructure geometry.

5 Conclusions

The combination of cycle tracks and protected intersections offers the promise of increasing road safety by separating bicyclists and vehicles along city blocks and by improving the lines of sight at intersection conflict points were the paths of turning vehicles cross the paths of bicyclists. Protected intersections displace the conflict point from the turning area, giving drivers a better view of bicyclists approaching the conflict area and riders a better view of vehicles approaching the conflict area.

This study examined the influence of road infrastructure on bicyclist riding behavior when they crossed intersections with turning traffic using a large-screen bicycling simulator. The results show significant differences in the margin of safety between riders and turning vehicles at the conflict point where their paths cross in protected vs. unprotected intersections. When riding on a protected intersection, riders had, on average, about 3 m more space between them and a turning vehicle than did riders in an unprotected intersection. This difference could give riders a greater opportunity to respond to potential collisions.

The results also show a greater separation between the car and bicyclist when the car entered the intersection for treatment vs. control conditions. This indicates that the experience of encountering cars that turned in front of the rider influenced how riders approached intersections.

A variety of factors may have contributed to the differences in how riders approached protected vs. unprotected intersections, including: (1) the geometry of the path caused riders to swerve as they entered protected interactions, and they may have reduced their speed to better negotiate the curved path, and (2) the displacement of the riders' path from the intersection in protected intersections may have given riders a better view of right-turning vehicles, which led them to reduce their speed. Whatever the underlying reason, the increased margin of safety points to potential safety gains with protected intersections relative to on-road bike lanes.

References

1. Jensen, S.U. (2008). *Bicycle tracks and lanes: A before-after study*. Transportation Research Board 87th Annual Meeting, Washington, D.C., U.S.
2. Rothenberg, H., Goodman, D., & Sundstrom, C. (2016). *Separated bike lane crash analysis*. Transportation Research Board 95th Annual Meeting, Washington, D.C., U.S.
3. Buehler, R., & Dill, J. (2016). Bikeway networks: A review of effects on cycling. *Transport Reviews, 36*(1), 9-27.
4. DiGioia, J., Watkins, K.E., Xu, Y., Rodgers, M., & Guensler, R. (2017). Safety impacts of bicycle infrastructure: A critical review. *Journal of Safety Research, 61*, 105-119.
5. Lusk, A.C., Furth, PG., Morency, P., Miranda-Moreno, L.F., Willett, W.C., & Dennerlein, J.T. (2011). Risk of injury for bicycling on cycle tracks versus in the street. *Injury Prevention, 17*(2), 131-135.
6. Thomas, B., & DeRobertis, (2013) M. The safety of urban cycle tracks: A review of the literature. *Accident Analysis & Prevention, 52*, 219-227.
7. Madsen, T. K. O., & Lahrmann, H. (2017). Comparison of five bicycle facility designs in signalized intersections using traffic conflict studies. *Transportation Research Part F: Traffic Psychology and Behaviour, 46*, 438-450.
8. Deliali, A., Campbell, N., Knodler, M., & Christofa, E. (2020). Understanding the safety impact of protected intersection design elements: A driving simulation approach. *Transportation Research Record*, https://trid.trb.org/view/1690026.
9. Warner, J., Hurwitz, D. S., Monsere, C. M., & Fleskes, K. (2017). A simulator-based analysis of engineering treatments for right-hook bicycle crashes at signalized intersections. *Accident Analysis & Prevention*, 104, 46-57.

10. Falbo, N. (n.d.). *Protected intersections for bicyclists.* http://www.protectedintersection.com/

11. MassDOT (2017). Intersection design. *MassDOT Separated Bike Lane Planning & Design Guide.* https://www.mass.gov/files/documents/2017/10/26/SeparatedBikeLaneChapter4_Intersections.pdf