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Operational Impacts of Protected-Permitted Right-Turn Phasing and Pavement Markings on Bicyclist Performance during Conflicts with Right-Turning Vehicles

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Abstract
Conflict between bicycles and right-turning vehicles on the approach to signalized intersections is a critical safety concern. To understand the operational implications of protected-permitted right-turn signal indications in conjunction with pavement markings on bicyclist performance, a full-scale bicycling simulator experiment was performed. Velocity and lateral position of bicyclists were evaluated during conflicts between bicycles and right-turning vehicles. A mixed factorial design was considered. Two within-subject factors were analyzed: the signal indication for right-turning vehicles with five levels (circular red, circular green, solid red arrow, solid green arrow, and flashing yellow arrow), and the pavement markings in the conflict area with two levels (white lane markings with no supplemental pavement color and white lane markings with solid green pavement applied in the conflict area). Additionally, the influence of gender as a between-subject variable was considered. Forty-eight participants (24 female) completed the experiment. Signal indications and pavement markings had statistically significant effects on bicyclist velocity and lateral position, but these effects varied at different factor levels. Additionally, during the conflicts, male participants were found to have higher velocity than female participants. This difference was not influenced by engineering treatments. The results provide guidance to transportation professionals about how traffic control devices could be applied to conflict areas on the approach to signalized intersections.

As traffic congestion grows in urban areas, many cities are encouraging bicycling as a functional alternative to automotive use. Bicycling is less infrastructure-intensive than public transportation and has a longer range than walking. Many states and cities within the U.S.A. have plans to increase their bicycle mode share. For example, California has adopted its first statewide active transportation plan with a goal of tripling the number of people who commute by bicycle between 2012 and 2020 (*1*), and Portland, OR, has adopted a Bicycle Plan which aims to achieve a 25% mode share by 2030 (*2*). However, the increasing popularity of bicycling has led to a greater frequency of conflicts between bicycles and motor-vehicles. In the U.S.A., despite a decrease in the total number of motor vehicle traffic fatalities, the proportion of bicyclist fatalities among total traffic fatalities increased from 1.47% in 2003 (629/42,884 bicyclist/total fatalities) to 2.24% in 2016 (840/37,461 bicyclist/total fatalities) (*3*). City streets and intersections constitute only a small fraction of the overall area of the surface transportation system. Nevertheless, a comparatively large number of crashes occur on city streets and intersections, which are locations where various transportation modes directly interact, sometimes in conflicting ways. The National Highway Traffic Safety Administration reported that in 2016, 71% of fatal crashes involving bicyclists in the U.S.A. occurred in urban areas. Among the bicycle-involved fatal crashes, 30% occurred at intersections, 58% at non-intersections, and 12% at other locations (*4*).

Previous studies show that to improve their safety in urban areas, bicyclists prefer route alternatives that

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create physical separation between bicycles and motor vehicle traffic (*5*). However, because of limited space in dense urban areas, physically separated bicycle lanes and buffered bicycle lanes are not always feasible. As such, conventional bicycle lanes, which designate an exclusive space for bicyclists through the use of pavement markings and signage, are frequently observed on city streets in dense urban environments. Conventional bicycle lanes are located adjacent to motor vehicle travel lanes and flow in the same direction as motor vehicle traffic (*6*).

Bicyclists in a conventional bicycle lane are positioned to the right of motorists. As such, signalized intersections with exclusive right-turn bays inherently incorporate a potential risk of crashes between bicycles and motor-vehicles. In fact, based on design practices in Oregon and recommendations by NACTO, when an intersection includes an exclusive right-turn bay, the bicyclist will pass a conflict point with right-turning vehicles before the intersection, after which they will be positioned to the left of motorists. Although motorists must legally yield right-of-way to bicyclists in bicycle lanes, motorists often do not look for bicyclists, look but do not see approaching bicyclists, or misjudge the gap of approaching bicyclists (*7*). Additionally, bicyclists do not always position themselves to be readily seen, or they approach intersections at high speeds (*8*).

The overall goal of this research was to evaluate the performance of bicyclists on the approach to a signalized intersection in a conventional bicycle lane and during conflicts with right-turning vehicles. Previous research shows that engineering treatments could have an impact on road user behavior at signalized intersections (e.g., *9–12*). Therefore, this study considered different configurations of signal phasing and bicycle lane pavement markings. Notably, this study analyzed the safety and operational implications of using protected-permitted right-turns (PPRTs) in conjunction with colored pavement markings. (In the State of Oregon, green colored pavement can be authorized by the Region Traffic Manager/Engineer for use on state highways per FHWA Interim Approval IA-14.) Additionally, male and female bicyclists have been found to have different preferences for bicycling and distinct performance on the road (e.g., *13*, *14*). Therefore, this study also considered the role of gender on bicyclist behavior during the aforementioned conflict.

While data from accident reports and field observations can be a helpful starting point, they can lack the detail necessary to comprehensively determine what factors contributed to a crash, such as bicyclist behavior, and it can be difficult to produce statistically significant conclusions. Even essential elements, such as the velocity and position of the parties involved, along with human factors, can be undocumented, making it difficult to study this problem from various perspectives. To account for these deficiencies, this research is unique in the way that it leveraged the high-fidelity full-scale bicycling simulator at Oregon State University (OSU) to investigate factors contributing to conflicts between bicycles and right-turning vehicles.

Background

The present study investigates how PPRT phasing and colored pavement markings affect bicyclist behavior on the approach to a signalized intersection in a full-scale bicycling simulator environment. Therefore, the related literature is reviewed in three individual sections: PPRT phasing, pavement markings, and bicycling simulation.

PPRT Phasing

There is a surprising absence of specific guidance or research on how right-turn phasing alternatives should be selected, and how they compare in relation to operational and safety performance. The Signal Timing Manual (*15*) considers overlaps for right-turn movements in the presence of exclusive right-turn lanes. In this case, the parent phase is typically the compatible left-turn phase. Right-turn movements are permitted when an adjacent pedestrian phase is called. When no pedestrians are present, the right-turn movement is protected and can be signaled with a solid green arrow (SGA) (*15*). In Oregon, a right-turn movement under a circular red (CR), or solid red arrow (SRA) indication is permitted after coming to a complete stop unless a posted sign states otherwise. Additionally, a right-turn movement on a circular green (CG) or flashing yellow arrow (FYA) is permitted with caution after yielding to pedestrians in the crosswalk. These movements are called permissive turns (*16*). Protected-only right turns, indicated by a SGA, are generally used for exclusive right-turn lanes and can run concurrently with any non-conflicting vehicular or pedestrian movement (*16*). Here, determination of right-turn signal phasing is based on engineering studies and various factors, such as capacity, right-turn volume, and the presence of congestion (or crashes), right-turn lane(s), and conflicting cross walk(s).

In one of the few studies on PPRT phasing, Australian researchers examined the safety of using partially to fully controlled right-turn phasing at signalized intersections. They concluded that when phasing was changed from partially to fully controlled, the number of crashes of any type decreased by 65%, and the number of right-through crashes decreased by 93% (*17*). Another study in China evaluated vehicle and pedestrian conflicts under exclusive right-turn phase setting. They concluded that, if the conflict probability occurring in the crosswalk between pedestrian and right-turning vehicles is higher than 0.6, setting an exclusive right-turn phase should be considered (*18*). In the U.S. context, Furth et al. (2014) examined appropriate phasing for right turns and pedestrian/bicycle crossings under conditions of high turn volume or high speed, focusing on protected right-turn phasing. They introduced a unique "protected-yet-concurrent" phasing scheme and concluded that the delay and right-of-way requirements were minimal for their phasing scheme, and that the complexity of the phasing plans, coordination, and possibility of using re-service would affect phasing performance (*19*). Additionally, Hurwitz et al. (2018) studied the safety and operational implications of using FYA in PPRT phasing through a driving simulator experiment. They suggested that implementation of a FYA instead of a CG could improve drivers' yielding behavior and pedestrian safety, especially at intersections with high volumes of permissive right turns (*20*).

Pavement Markings

Pavement markings can be installed to help reinforce routes and directional signage and to provide bicyclist positioning and route branding benefits (*21*). Colored pavement within a bicycle lane increases visibility of the facility, identifies potential areas of conflict, and reinforces priority to bicyclists in conflict areas (*6*). In relation to pavement markings to improve right-of-way negotiations between bicyclists and right-turning vehicles, the National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide* (*6*) is one of the most comprehensive resources. It identifies three different crossing features that may be used, including a combination of several features (Figure 1). Pavement color or the negative space between two sections of pavement color increases the visibility of bicyclists and bicycle infrastructure, and the dashed white lines indicate that merging is permitted.

Bicycling Simulators

The bicycling simulator has been one of the more challenging simulators to develop because of the inherently unstable dynamics of the bicycle coupled with the dynamics of the human rider, and because of the difficulties associated with the real-time simulation of human-controlled and human-powered vehicles moving in a virtual environment (*22*). The major elements of a typical bicycling simulator include: cueing systems (visual, auditory, proprioceptive, and motion), bicycle dynamics, computers and electronics, bicycle frame and control, measurement algorithms, and data processing and storage (*23*). Different forms of bicycling simulators have been utilized in medical science (e.g., *24*), sport science (e.g., *25*), and mechanical engineering (e.g., *26*). However, very few studies have employed full-scale bicycling simulators in the context of transportation safety.

In the U.S.A., bicycling simulators have been used at the University of Iowa (*27*) and the University of Missouri (*28*) to conduct studies in transportation safety. Hank Lab Researchers at the University of Iowa have extensively employed a bicycling simulator to investigate different aspects of the road-crossing behavior of child and adult bicyclists (e.g., *29–31*). For instance, Plumert et al. examined how child and adult bicyclists' gap choices and movement timing changed over a single experimental session in response to general and specific experience with crossing traffic-filled intersections in a virtual environment and found that gap acceptance shifted in response to traffic density (*32*). A fully instrumented bicycling simulator has been also used by researchers at the University of Missouri to study bicyclist behavior. Brown et al. investigated the use of alternative pavement markings for bicycle wayfinding and proper bicycle placement at intersections in the fully instrumented bicycling simulator at the University of Missouri and found that wayfinding markings with a green background performed better than other alternatives (*33*).

Method

OSU Bicycling Simulator

OSU features a bicycling simulator consisting of an instrumented urban bicycle placed on top of an adjustable stationary platform (Figure 2). A 3.20 m × 2.54 m screen provides the forward view with a visual angle of 109° (horizontally) × 89° (vertically) and image resolution of 1024 × 768 pixels. In addition, a small window on the top left corner of the screen acts as a rear-view mirror (*34*). Researchers build the environment and monitor subject bicyclists from the operator workstation (Figure 2) which is in a separate room, adjacent to the simulator platform.

The update rate for the projected graphics is 60 Hz. Ambient sounds around the bicycle are modeled with a 5.1 Logitech surround sound system. The computer system consists of a quad core host running Realtime Technologies SimCreator Software with a 60 Hz graphics update rate. The simulator software is capable of capturing and outputting accurate values for performance measures such as velocity, position, brake, and acceleration. The virtual environment was developed using simulator software packages, including Internet Scene Assembler (ISA), Simcreator, AutoCAD, and Google Sketchup.

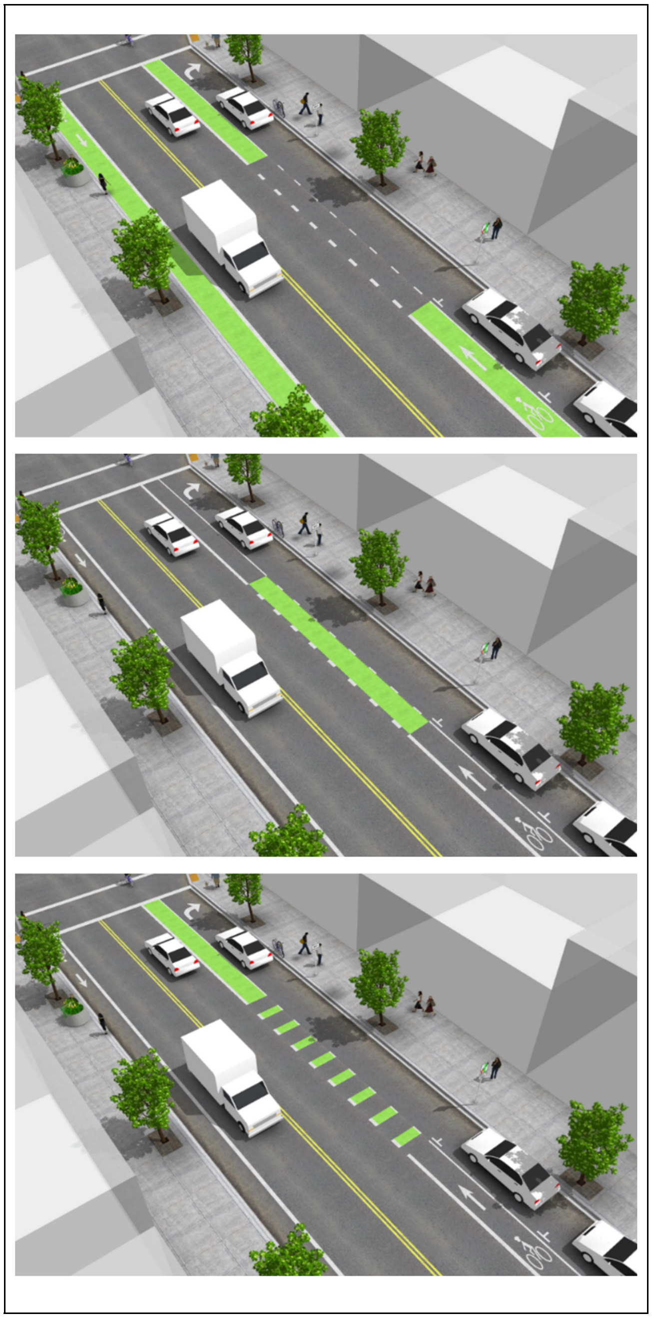

Figure 1. Three levels of pavement marking for right-turn conflicts according to NACTO *Urban Bikeway Design Guide* (*6*).

The simulated test track was developed in ISA using Java Script-based sensors on the test tracks to display dynamic objects, such as a right-turning vehicle cutting in front of a bicyclist or a pedestrian walking on a sidewalk.

Treatment Options

Two independent variables are included in the experiment: colored pavement markings and right-turn signal indications. According to the literature, for pavement marking levels, recommendations from the NACTO *Urban Bikeway Design Guide* (*6*) were considered. Two levels of bicycle lane pavement markings were used: (a) white lane markings with no supplemental pavement color (called "white lane markings" hereafter) (Figure 3*a*), and (b) white lane markings with solid green pavement applied in the conflict area (called "solid green" or "solid green pavement" hereafter) (Figure 3*b*). In accordance with Oregon State regulations, five levels of signal indication were considered such that the impact of PPRT phasing could be further analyzed: CR, CG, SRA, SGA, and FYA.

Research Questions

Bicyclist performance was captured in relation to velocity (m/s) and lateral position (m), which were measured over a fixed segment of the road prior to the conflict point. The potential influence of the experimental factors on each response variable formed the basis of the research questions (RQs) regarding bicyclist performance. Additionally, this study investigated whether male and female bicyclists perform differently under different configurations of engineering treatments:

- RQ1: Do pavement markings and signal indications affect the velocity of the bicyclist?
- RQ2: Do pavement markings and signal indications affect the lateral position of the bicyclist?
- RQ3: Does bicyclist gender affect velocity or lateral position during the conflicts with right-turning vehicles?

Experimental Design

The bicycling simulator experiment was designed to examine conflicts between right-turning vehicles and bicycles by analyzing bicyclist behavior at signalized intersections. Specifically, 2.5 s before the bicyclist reached a conflict area, a right-turning vehicle cut in front of the bicyclist. This cut-in time gap of 2.5 s is based on an accepted design value for the reaction times of motorists and bicyclists (*35*). The simulated signalized intersection operated as pre-timed and the right-of-way was simultaneously assigned to or removed from through movements and right-turning vehicles. The desired signal indication was displayed when bicyclists were 100 m upstream of the intersection. In the case of the green indication, the right-of-way was allocated to bicyclists until they completely cleared the intersection. In case of the red indications, right-of-way was assigned to the bicyclist 7 s after they passed a proximity sensor located in the middle of conflict area. Motor vehicle activity was

Figure 2. Views of the OSU bicycling simulator (*a*) and operator work station (*b*).

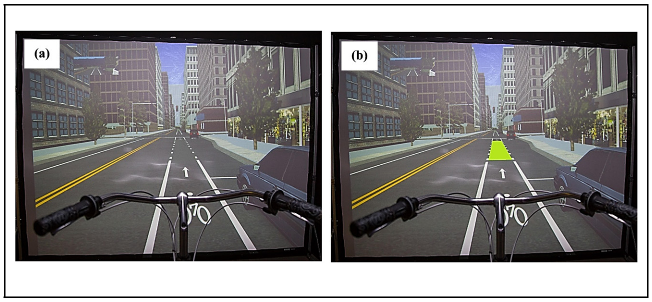

Figure 3. Two levels of pavement marking in experimental design: (*a*) white lane markings and (*b*) solid green.

kept at a low level and it was identical in all of the scenarios.

The independent variables (factors) and levels resulted in a 2 × 5 factorial design. The roadway cross-section included two 3.66 m travel lanes with 1.83 m bicycle lanes in each direction. A 2.44 m parking lane interrupted by a 3.66 m right-turn bay was created in one direction to account for conflicts between bicycles and right-turning vehicles.

Ten scenarios were presented to participants across four grids, with participants exposed to various treatment configurations to measure their influence. To control for practice or carryover effects, the order of presentation of the intersection grids was counterbalanced and the placement of scenarios on each grid was randomly assigned (*36*, *37*).

Participants

Study participants were recruited from the community in and around Corvallis, Oregon, and every effort was made to recruit a representative sample of Oregon bicyclists. The simulator experiment was successfully completed by 48 participants, including 24 women (M_{age} = 29.71, SD_{age} = 10.03) and 24 men (M_{age} = 28.42, SD_{age} = 11.90). Participants most frequently bicycled on a daily basis (52.1%), to commute to work/school (72.9%), and they bicycled for 10 to 20 min on an average trip (50.0%). Additionally, over 83% of participants had experience of bicycle riding in a busy downtown environment.

Results

Because each participant was exposed to all possible combinations of independent variables, mixed repeated-measure ANOVA tests were performed with pavement marking and signal indication as within-subject factors and gender as a between-subject factor. Bicyclist velocity and lateral position were analyzed separately as dependent variables. Mauchly's sphericity test was used to confirm sphericity assumptions. A significance level of 0.05 was adopted. Pairwise comparisons of estimated marginal means with a Bonferroni adjustment were conducted whenever a significant effect was observed. Effect

Table 1. Descriptive Statistics of Velocity (m/s) at each Level of each Independent Variable

		White lane markings		Solid green	
Signal indication	Descriptive statistics	Women	Men	Women	Men
CR	*M*	4.67	5.14	3.96	4.63
	(*SD*)	(0.76)	(0.74)	(0.85)	(0.80)
CG	*M*	5.31	5.64	4.45	4.91
	(*SD*)	(0.83)	(0.95)	(0.97)	(0.88)
SRA	*M*	4.70	5.23	4.51	5.10
	(*SD*)	(0.76)	(0.77)	(0.82)	(0.77)
SGA	*M*	4.64	4.96	5.10	5.42
	(*SD*)	(0.84)	(1.03)	(0.84)	(0.80)
FYA	*M*	4.77	5.17	4.99	5.43
	(*SD*)	(1.03)	(1.12)	(0.82)	(0.91)

size was reported by using partial eta squared. IBM SPSS Statistics software version 24 was used for data analysis.

Velocity

Mean (M) and standard deviation (SD) values for velocity at each level of each independent variable are reported in Table 1. Bicyclists had the highest mean velocity where no engineering treatment was applied around the conflict area (white lane markings only) and the signal indication was CG (women: $M_{Velocity} = 5.31$ m/s, $SD_{Velocity} = 0.83$ m/s; men: $M_{Velocity} = 5.64$ m/s, $SD_{Velocity} = 0.95$ m/s). Participants encountering a CR while bicycling on a solid green bicycle lane had the lowest mean velocity (women: $M_{Velocity} = 3.96$ m/s, $SD_{Velocity} = 0.85$ m/s; men: $M_{Velocity} = 4.63$ m/s, $SD_{Velocity} = 0.80$ m/s).

Mixed repeated-measure ANOVA tests were used to determine the effects of factors on mean bicyclist velocity. Pairwise comparisons were conducted to find the origin of the difference whenever a significant effect was observed. As shown in Table 2, pavement marking (F(1, 46) = 8.179, $P = 0.006$), signal indication (F(4, 184) = 16.962, $P < 0.001$), and gender (F(1, 46) = 4.618, $P = 0.037$) had significant main effects on bicyclist velocity. There was also a statistically significant interaction between the combined effects of pavement marking and signal indication on bicyclist velocity (F(4, 184) = 33.219, $P < 0.001$). In relation to independent variables, the interaction of pavement marking and signal indication had the highest effect on bicyclist velocity, with about 42% of within-subject variance being accounted for by this interaction.

By using Bonferroni-corrected post-hoc tests for pairwise comparison of the main effect of pavement marking, it was found that regardless of the type of signal indication and bicyclist gender, participants cycled more slowly on solid green bicycle lanes ($P = 0.006$). Pairwise comparisons for the main effect of signal indication also showed that, regardless of the type of pavement marking and gender, participants encountering a CR indication cycled significantly more slowly than bicyclists encountering any other signal indication ($P < 0.001$ for all pairwise comparisons). No significant difference was observed for other levels of signal indication. Finally, pairwise comparison for the main effect of gender showed that, regardless of pavement marking or signal indication, women cycled more slowly than men ($P = 0.006$).

Two-way interactions were considered in the pairwise comparison for pavement marking and signal indication. Figure 4 plots the estimated marginal mean velocity at each level of pavement marking and signal indication. Pairwise comparisons showed, that regardless of gender, participants cycled significantly more quickly with white lane markings than with solid green for CR ($P < 0.001$), CG ($P < 0.001$), and SRA ($P = 0.021$). Participants cycled significantly more slowly with white lane markings than with solid green for SGA ($P < 0.001$) and FYA ($P = 0.041$).

Considering the application of PPRT phasing, pairwise comparison results showed that, with the white lane markings in place, there was no statistically significant difference between CR and SRA ($P = 0.325$); however, participants encountering a CG had a significantly higher velocity than those encountering a FYA ($P < 0.001$). With solid green pavement markings in place, participants had a significantly higher velocity for the SRA than for the CR ($P < 0.001$) and for the FYA compared with the CG ($P < 0.001$).

Lateral Position

Descriptive statistics of the lateral position for each independent variable level are reported in Table 3. The right edge of the bicycle lane was defined as 0 m, making the left edge 1.83 m. Women had the least divergence from the right edge of the bicycle lane when no colored pavement marking was used (only white lane markings)

Table 2. Mixed Repeated-Measure ANOVA Results on Velocity (m/s)

Source	$F(v_1, v_2)$	P	η_p^2
Within-subject factors			
Pavement marking	8.179 (1, 46)*	0.006	0.151
Signal indication	16.962 (4, 184)*	< 0.001	0.269
Pavement marking × Signal indication	33.219 (4, 184)*	< 0.001	0.419
Between-subject factors			
Gender	4.618 (1, 46) *	0.037	0.091
Gender × Pavement marking	0.534 (1, 46)	0.468	0.011
Gender × Signal indication	1.134 (4, 184)	0.342	0.024
Gender × Pavement marking × Signal indication	0.182 (4, 184)	0.948	0.004

Note: F denotes F statistic; v1 and v2 denote degrees of freedom; η_p^2 denotes partial eta squared.
*Statistically significant at 95% confidence interval.

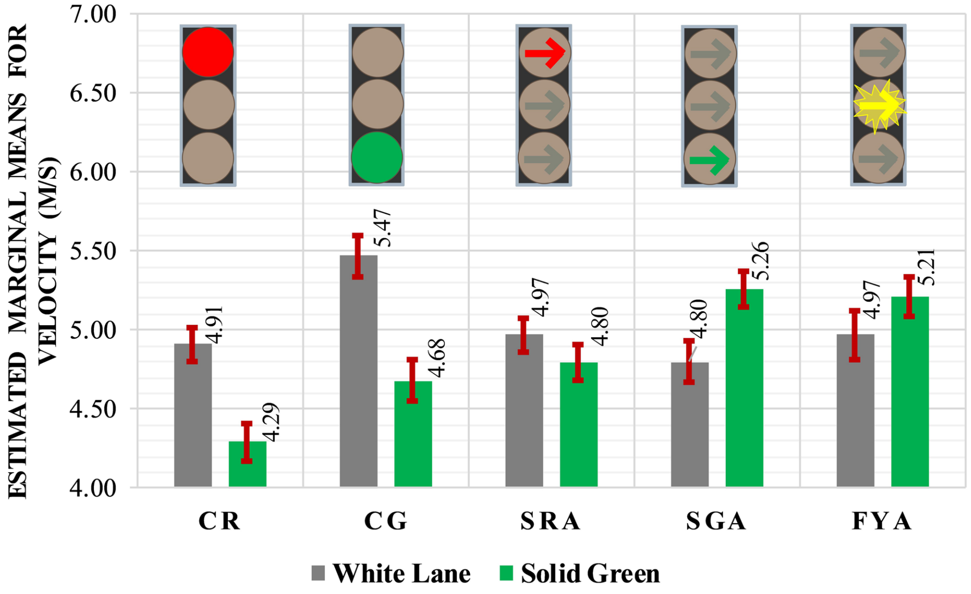

Figure 4. Statistically significant two-way interactions on velocity, by ANOVA.

Table 3. Descriptive Statistics of Lateral Position (m) at each Level of each Independent Variable

		White lane markings		Solid green	
Signal indication	Descriptive statistics	Women	Men	Women	Men
CR	*M*	0.67	0.64	0.59	0.60
	(*SD*)	(0.18)	(0.14)	(0.15)	(0.14)
CG	*M*	0.81	0.75	0.62	0.59
	(*SD*)	(0.21)	(0.17)	(0.16)	(0.15)
SRA	*M*	0.65	0.64	0.69	0.63
	(*SD*)	(0.16)	(0.15)	(0.18)	(0.11)
SGA	*M*	0.58	0.60	0.68	0.63
	(SD)	(0.14)	(0.18)	(0.30)	(0.14)
FYA	*M*	0.70	0.71	0.70	0.65
	(*SD*)	(0.18)	(0.23)	(0.22)	(0.16)

Table 4. Mixed Repeated-Measure ANOVA Results on Lateral Position (m)

Source	$F(v_1, v_2)$	P	η_p^2
Within-subject factors			
Pavement marking	11.953 (1, 46)*	0.001	0.206
Signal indication	8.700 (4, 184)*	< 0.001	0.159
Pavement marking × Signal indication	11.451 (4, 184)*	< 0.001	0.199
Between-subject factors			
Gender	0.383 (1, 46)	0.539	0.008
Gender × Pavement marking	0.685 (1, 46)	0.412	0.015
Gender × Signal indication	0.429 (4, 184)	0.787	0.009
Gender × Pavement marking × Signal indication	1.027 (4, 184)	0.395	0.022

Note: F denotes F statistic; v1 and v2 denote degrees of freedom; η_p^2 denotes partial eta squared.
*Statistically significant at 95% confidence interval.

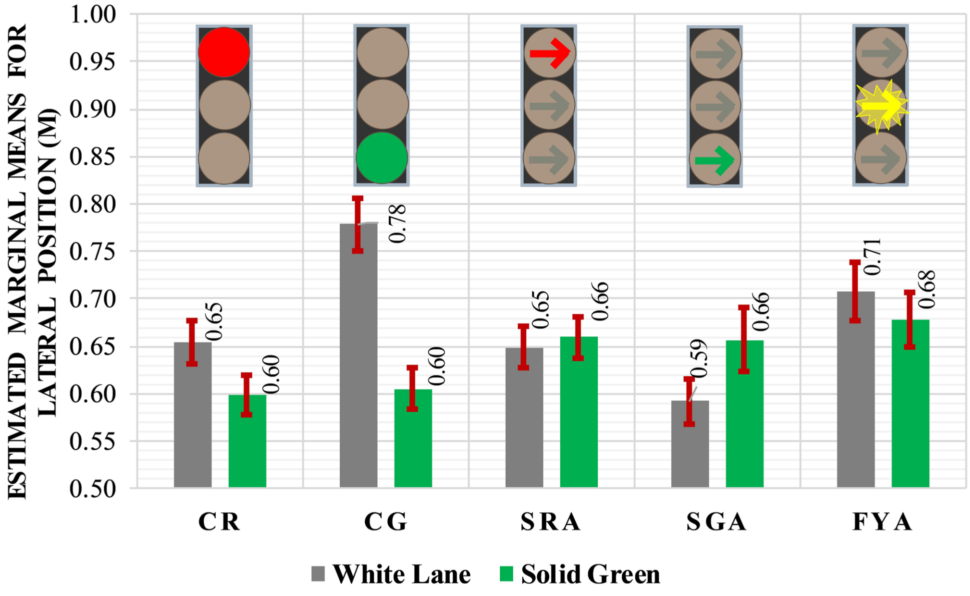

Figure 5. Statistically significant two-way interactions on lateral position, by ANOVA.

and the signal indication was a SGA ($M_{Lateral}$ = 0.58 m, $SD_{Lateral}$ = 0.14 m). Men had the least divergence from the right edge of the bicycle lane under two different conditions: (a) when white lane markings were used in conjunction with a SGA ($M_{Lateral}$ = 0.60 m, $SD_{Lateral}$ = 0.18 m), and (b) when solid green was used in conjunction with a CR ($M_{Lateral}$ = 0.60 m, $SD_{Lateral}$ = 0.14 m). Participants of both genders encountering a CG while in a bicycle lane with white lane markings had the most divergence from the right edge of the bicycle lane (women: $M_{Lateral}$ = 0.81 m, $SD_{Lateral}$ = 0.21 m; men: $M_{Lateral}$ = 0.75 m, $SD_{Lateral}$ = 0.17 m).

Mixed repeated-measure ANOVA tests were used to determine the effects of factors on the mean lateral position of bicyclists, with pairwise comparisons used to find the origin of any significant difference. As shown in Table 4, pavement marking (F(1, 46) = 11.953, P = 0.001) and signal indication (F(4, 184) = 8.700, $P < 0.001$) had significant main effects on the lateral position of the bicyclist. There was a statistically significant interaction between the combined effects of pavement marking and signal indication on lateral position (F(4, 184) = 11.451, $P < 0.001$). In relation to independent variables, pavement marking had the greatest effect on lateral position and accounted for about 21% of within-subject variance.

Results of Bonferroni-corrected post-hoc tests, used for pairwise comparison of the main effect of pavement marking, showed that, regardless of the type of signal indication and bicyclist gender, participants had a significantly lower divergence from the right edge on solid green bicycle lanes (P = 0.001). Pairwise comparisons for the main effect of signal indication showed, that regardless of the type of pavement marking and gender, participants encountering a CR or SRA indication had a significantly lower divergence compared with those encountering a CG ($P < 0.001$ for CR and P = 0.001 for SRA) or FYA indication (P = 0.009 for CR and P = 0.003 for SRA). No significant difference was observed for other levels of signal indication.

Table 5. Summary of Findings from Within-Subject Variation Analysis of Bicycling Simulation Experiment

Pavement markings	CR vs. SRA	CG vs. FYA
White lane markings with no supplemental colored pavement	$V^*_{CR} \equiv V_{SRA}$ $L^*_{CR} \equiv L_{SRA}$	$V_{CG} > V_{FYA}$ $L_{CG} > L_{FYA}$
White lane markings with solid green	$V_{CR} < V_{SRA}$ $L_{CR} < L_{SRA}$	$V_{CG} < V_{FYA}$ $L_{CG} < L_{FYA}$

Note: * V denotes velocity; L denotes lateral position.

Two-way interactions were considered in the pairwise comparison for pavement marking and signal indication. Figure 5 plots the estimated marginal means of lateral position at each level of pavement marking and signal indication. Regardless of gender, participants had a significantly higher divergence in white lane markings than in solid green pavement for CR ($P = 0.011$) and CG ($P < 0.001$). Participants had a significantly lower divergence in white lane markings than in solid green pavement for SGA ($P = 0.044$) and FYA ($P = 0.041$).

Regarding the application of PPRT phasing, pairwise comparison results showed that with white lane markings in place there was no statistically significant difference between a CR and SRA ($P = 0.694$), but participants encountering the CG had a significantly higher divergence than those encountering the FYA ($P = 0.033$). With solid green pavement markings in place, participants had a significantly higher divergence for SRA than for CR ($P = 0.003$) and for FYA than for CG ($P = 0.003$).

Discussion

The results of this study demonstrated a consistent narrative related to how bicyclists interact with right-turning vehicles on the approach to signalized intersections, and how different levels of engineering treatments are effective. Overall, the results showed that the application of PPRT does affect bicyclist performance, and this effect varies based on the pavement markings employed. Effect size values also revealed interesting findings regarding the magnitude of the influence of the studied variables. In comparing main effects, one can find that pavement markings had the largest impact on bicyclist velocity, while signal indication had the largest impact on lateral position. This finding implies that different engineering treatments should be prioritized differently, depending on the target bicyclist behavior desired at a particular location.

The simultaneous effect of pavement markings and signal indication was found to be statistically significant for both velocity and lateral position. This fact is well demonstrated in the effect size values as the interaction of these two variables accounts for high variance in velocity and lateral position. Notably, when the SRA indication was used instead of the CR, with no colored pavement marking (white lane marking only), no difference was observed in bicyclist behavior. However, when solid green pavement markings were applied to the conflict area, bicyclists tended to travel at faster speeds and to position themselves more toward the travel lane. On the other hand, when the FYA indication was used instead of the CG, with no colored pavement markings (white lane marking only), bicyclists traveled more slowly and stayed further away from the travel lane. However, with solid green pavement markings applied to the conflict area, the bicyclist traveled more quickly and diverted more toward the travel lane. Table 5 summarizes the findings from the within-subject variation analysis of the bicycling simulation experiment.

Gender was found to influence some aspects of bicyclist performance. According to effect size values, while gender accounted for more than 9% of between-subject variation of velocity, it accounted for just 0.8% of between-subject variation of lateral position. Specifically, regardless of signal indication and pavement markings, male bicyclists had a significantly higher velocity than female bicyclists during conflict with right-turning vehicles. Gender did not have any impact on bicyclist lateral position, however. None of the interactions between gender and engineering treatments were found to be statistically significant. This suggests that the impact of PPRT phasing and colored pavement markings are perceived similarly for men and women bicyclists.

Summary and Conclusion

The overall goal of this research was to improve bicyclist safety in the vicinity of urban intersections. Bicyclist performance during conflicts between bicycles and right-turning vehicles on the approach to signalized intersections was evaluated, and the safety and operational implications of using PPRT phasing in conjunction with colored pavement markings were analyzed. The bicycling simulator experiment was designed to examine conflicts between right-turning vehicles and bicycles by analyzing bicyclist performance. Specifically, 2.5 s before the bicyclist reached a conflict area, a right-turning vehicle cut in

Table 6. Practical Implications of PPRT Phasing and Pavement Markings on Bicyclist Performance

	Initial condition		Secondary condition		Bicyclist performance	
Case	Pavement marking	Signal indication	Pavement marking	Signal indication	Velocity	Lateral position
A	White lane markings	CR	White lane markings	SRA	Equal	Equal
B	Solid green	CR	Solid green	SRA	Increase	Increase
C	White lane markings	CG	White lane markings	FYA	Decrease	Decrease
D	Solid green	CG	Solid green	FYA	Increase	Increase

front of the bicyclist. A 2 × 5 factorial design was set up with two levels of bicycle lane pavement markings (white lane marking and solid green) and five levels of signal indication (CR, CG, SRA, SGA, and FYA). Bicyclist performance was measured in relation to velocity (m/s) and lateral position (m). In addition to engineering treatments, the role of gender on bicyclist performance was also investigated. The simulation experiment was successfully completed by 48 participants, 24 women and 24 men. Mixed repeated-measures analysis of variance (ANOVA) was used to study the effect of pavement markings, signal indication, and gender on bicyclist performance.

The findings of the present study suggest that influence of PPRT phasing on bicyclist performance is contingent upon the type of pavement markings applied to the conflict area. Table 6 presents changes in bicyclist behavior as the result of a concurrent change in signal indication or pavement markings. These findings could be used by transportation engineering practitioners to incorporate bicyclists' needs better in their design.

When the solid green pavement markings were used, exchanging typical signal indications with PPRT phasing (CR with SRA in Case B, and CG with FYA in Case D) negatively affected conflicts between bicyclists and right-turning vehicles by increasing the velocity of bicyclists and causing them to move closer to the travel lane (increase in lateral position). When no colored pavement markings were used, replacing the CR with the SRA (Case A) had no effect on bicyclist behavior, but replacing the CG with the FYA (Case C) improved bicyclist safety by decreasing the velocity of the bicyclist and causing them to move further away from the travel lane (decrease in lateral position).

While surrogate safety measures could be extracted from findings of the present study, the direct safety implications of the engineering treatments have to be investigated in a separate study. The current study considered higher velocity and higher divergence from the right edge of bicycle lane to have a negative influence on bicyclist safety around right-turning vehicles at signalized intersections. It might be argued, however, that a higher velocity could reduce the amount of time in which bicyclists are exposed to the conflict area, and riding closer to the traffic lane could increase the visibility of the bicyclist and could therefore potentially increase bicyclist safety. Such possibilities should be investigated in future to help understand better the direct safety benefits of engineering treatments.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: MGA and DSH; data collection: MGA; analysis and interpretation of results: MGA and DSH; draft manuscript preparation: MGA and DSH. Both authors reviewed the results and approved the final version of the manuscript.

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