Experimental Research on Bicycle Safety Measures at Signalized Intersections

Abdul Rahman ABDUL RAHIMI[a], Aya KOJIMA[b], Hisashi KUBOTA[c]

[a, b, c] *Graduate School Science & Technology, Saitama University, Saitama, 338-8570, Japan*
[a] *E-mail: rahimi@dp.civil.saitama-u.ac.jp*
[b] *E-mail: kojima@dp.civil.saitama-u.ac.jp*
[c] *E-mail: hisashi@dp.civil.saitama-u.ac.jp*

Abstract: Nowadays, various signalized intersections with bicycle lanes designs are available for implementation. However, no safety comparisons have been made between these various designs. Therefore, it is necessary to compare the various designs available. In this study, intersection designs from Western countries are investigated to determine the safety measures available. Then the safety and comfort are compared with left-hooks being focused. Five patterns were selected including (1) Mixed traffic with left-turning motorist; (2) Left-turn in the intersection for motorist; (3) Bicycle signal; (4) Advanced stop lines for bicycles; and (5) Bicycle box. The five intersection patterns were prepared at an experiment site, and human subjects consisting bicyclist and motorist were traveled on the specified route freely. Questionnaire surveys and video observations were used for data analyses. The results show that (1) Mixed traffic with left-turning motorist is the safest and (3) Bicycle signal is the most comfortable intersection design.

Keywords: Bicycle, Bicycle Lane, Bicycle Safety, Early Start, Left-hook, Signalized Intersection

1. INTRODUCTION

Bicycle motor vehicle (BMV) accidents have a possibility to increase in Japan. The distances of bicycle lanes in Japan are increasing from year to year – 28,200 meters in 2009 (MLIT, 2010) and 29,583 meters in 2010 (MLIT, 2011) increasing bicycle safety from reduced crashes and injuries (Reynolds *et al.*, 2009) and bicyclists on the road are expected to increase by the implementation of bicycle lanes with the right circumstances (Dill and Carr, 2003). Furthermore, presently bicycles are required to cycle on the roadways instead on the sidewalk in Japan (MLIT and NPA, 2012) increasing bicycle safety since cycling on the road has a lower risk of accidents (Wachtel and Lewinson, 1994) and other bicycle related events (Aultman-Hall and Adams, 1998) than cycling on the sidewalks, which may also increase the number of bicyclists on the road. Bicycle accidents at signalized intersection are relative to the average daily bicycle volume (Reynolds *et al.*, 2009). Therefore, there is a possibility for BMV accidents to increase in Japan from the increasing number of bicyclists.

Signalized intersections are accident prone locations with many influencing factors (Wang and Nihan, 2004) and generally signalized intersections are very dangerous and should be avoided (PRESTO, 2010). In 2006, 20 percent of bicycle related accidents occurred at signalized intersections (JAMA, 2009). Bicyclists are less likely to be attributed to inattention and misjudgment in BMV accidents (Karl and Li, 1996). On the other hand, motorists are more likely to fail to yield, engage in improper overtaking, or to follow too closely before involving in BMV accidents (Karl and Li, 1996) with looked-but-failed-to-see and different gap acceptance of motorists influenced from other vehicles may also be factors contributing to BMV accidents at bicycle prioritized locations (Hersland and Jorgensen, 2002).

Safety and comfort are one of the two requirements of quality bicycle infrastructure besides directness, cohesion and attractiveness (CROW 2006; PRESTO, 2010) with contradictions between those requirements, though safety is the must highest priority (PRESTO, 2010). Bicyclists have a bigger risk and higher possibility of fatality when involved in traffic accidents. Bicyclists together with pedestrians and motorcyclists are vulnerable road users since they do not benefit external protective devices (Constant and Lagarde, 2010). In addition, typical vehicles have a higher momentum than bicycles from bigger mass and higher speed (Reynolds *et al.*, 2009) than bicycles. Thus, safe bicycle infrastructure is necessary to have a quality bicycle infrastructure because bicycles suffer higher risk of injuries and serious damage when accident occurs.

Implementing infrastructure modifications have a major advantage that is providing injury preventions without requiring action by the users or repeated reinforcement (Reynolds *et al.*, 2009). Until now, Western countries and cities had proposed and implemented various signalized intersection designs for the safety and comfort of bicyclist such as bicycle-vehicle combined lane designs and early start designs. Studies have been conducted on various signalized intersection designs (Hunter, 2000; Dill *et al*, 2012) and the results are positive. Existing literature also suggested that these signalized intersection designs will increase the safety of bicycles on the road (CROW. 2006, PRESTO 2010; NACTO, 2012).

Though, most studies are conducted separately not knowing the comparative effectiveness of these various bicycle related facilities. Moreover, no guidelines are available to indicate the appropriate signalized intersection designs from various signalized intersection designs available. Nevertheless, there is a possibility for bicyclists to have different perspectives between comfort and safety on bicycle facilities increasing the complication of the subject. In this study, various intersection designs with bicycle lanes are experimented to compare the comparative effectiveness of each design based on comfort and safety.

Left-hook accidents are focused in this study because 60 percent of the 20 percent bicycle related accidents at signalized intersection in 2006 occurred during right and left turns (JAMA, 2009). Left hooks accidents are accidents where a left-turning motorist strikes a bicyclist who is trying to continue straight through an intersection (Johnson, 2011).

The first objective of this study is to investigate various signalized intersection designs with bicycle lanes from various bicycling developed countries or areas to determine the safety measures available. The second objective of this study is to determine the feasible intersection designs by comparing safety and comfort of the design particularly focusing on left-hook accidents.

2. SIGNALIZED INTERSECTION DESIGNS

Traffic control, designs before and at intersections, and signal control has been implemented at signalized intersections with bicycle lanes in Western countries. The outline of various states of the intersections will be described in this section.

Traffic control signalized intersection designs includes combined bicycle lane/vehicle turn lane and left turning vehicle turn in intersections from prohibition to enter bicycle lane before the intersection. By combining bicycle lane and vehicle turn lane at signalized intersections, motorists are encouraged to yield to bicycles and to turn with a lower speed at intersections while reducing left-hook accidents (NACTO, 2012). Combined bicycle lane/vehicle turn lanes are also able to guide bicycles in situations where bicycle lanes are discontinued and to travel in the slower vehicle traffic maintaining comfort and priority of bicycles (NACTO, 2012).

Weaving of bicycles or/and vehicles from the overlapping bicycle lanes or vehicles lanes on one another to complement exclusive left-turn vehicle lanes are the signalized intersection designs before intersections investigated in this study. Bicycles are able to have a stacking lane to clarify their position and greater traffic flow (CROW, 2006). Though it is unsafe for bicycles because there are more lanes and motorist can overlook bicycles focusing on traffic control systems and busy traffics (CROW, 2006). In addition, there is a possibility for through bicycles blocking left-turning vehicles where left-turn vehicle capacity is necessary (Portland, 2010).

Designs at intersections and signal control investigated in this study are designs to give early start to bicycles. Early start or head start signalized intersection designs provides bicycles an earlier start than vehicles either from separated traffic signal (Transport for London, 2005; CROW, 2006; PRESTO, 2010; NACTO, 2012) or by positioning bicycles ahead of vehicles at signalized intersections (VicRoads, 2000; Transport for London, 2005; CROW, 2006; City of Portland, 2010; PRESTO, 2010; NACTO, 2012) improving safety of bicycles by positioning bicycles in motorists' field of vision to increase visibility of bicycles from vehicles and limiting blind spot of motorists on bicycles (CROW, 2006) and increasing comfort by prioritizing bicycles over vehicles (NACTO, 2012). The three early start signalized intersection designs examined in this study are bicycle signal, advanced stop line (ASL) and bicycle box.

2.1 Combined Bicycle Lane/Vehicle Turn Lane

Combine bike lane/vehicle turn lanes are combined suggestion bicycle lanes (dashed bicycle lanes in America and in the Netherlands) and exclusive left-vehicle turn lanes before the intersection to position suggestion bicycle lanes inside vehicle turn lanes (NACTO 2012) or to permit vehicles to enter bicycle lanes for a left-turn (AASHTO 2012). Combine bike lane/vehicle turn lane indicates and reminds merging movement can be expected in the merging areas commonly (NACTO, 2012; AASHTO 2012) called as mixing zones (NACTO, 2012) to encourage lane crossings in a merging fashion before intersections (Kane County, 2012). (Figure 1)

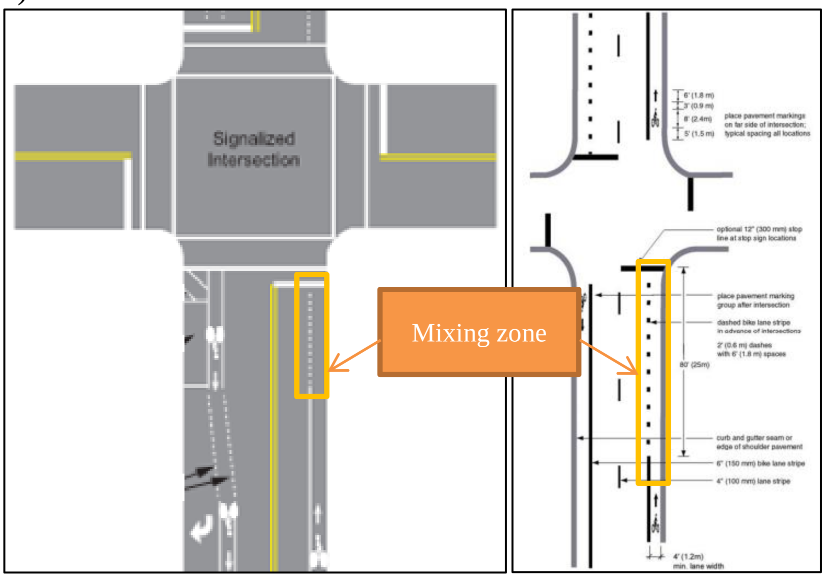

Figure 1. Combined bicycle lane/vehicle turn lane
(Left: AASHTO,2012; Right: Kane County, 2012)

2.2 Left-turning Vehicles Prohibited to Enter Bicycle Lane before Intersection

Here, the travel space of bicycles was maintained until the signalized intersection by prohibiting vehicles from encroaching into the bicycle lane from changing prohibition markings (yellow markings in Japan). Left-turning vehicles are only allowed to turn inside the intersection and prohibited from moving closer to the curb before the intersection.

2.3 Weaving of Bicycles or/and Vehicles

Here, bicycles or/and vehicles weave to the overlapping bicycle lanes or vehicle lanes on one another to assist through bicycles in the appropriate approach lane position and to indicate left-turning vehicles to expect and yield towards bicycles before reaching the intersection with designated exclusive left-turn vehicle lanes (VicRoads, 2001; CROW, 2006; City of Portland, 2010; Kane County, 2012). Bicycle lanes are ended by changing the markings to allow vehicles to weave through the bicycle lanes (dashed markings in America). (Figure 2)

2.4 Early Start Time and Early Stop Time by Bicycle Signal

Bicycle signal is an electrically powered traffic control device with bicycle signal heads used in combination with an existing conventional traffic signal (NACTO, 2012) typically using standard green, yellow and red lenses three-lens signal heads (City of Portland, 2010) to give early start (CROW, 2006), leading bicycle interval (NACTO, 2012) or pre-signals (Transport for London, 2005) to bicycles which is an earlier green signal for bicycles before other traffic. On the other hand, early stop is an earlier red signal for bicycles before other traffic (Pan and Cheng, 2011). (Figure 3)

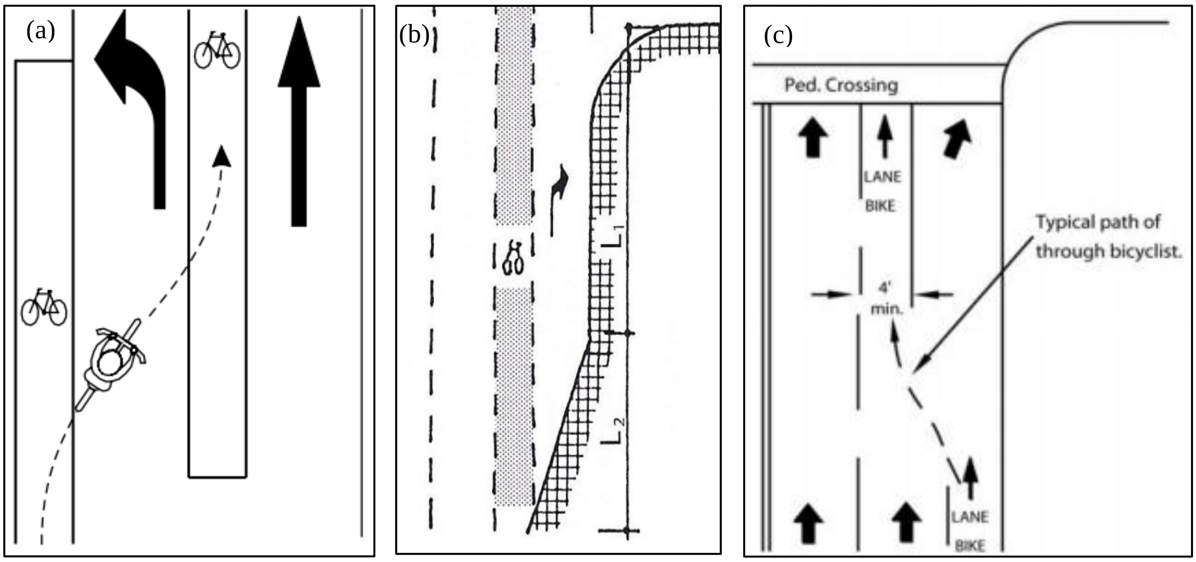

Figure 2. Left – Bicycles weave through vehicle lanes (VicRoads, 2001); Center – Vehicles weave through bicycle lanes (CROW, 2006); Right – Vehicles and bicycles weave through both lanes (Caltrans, 2006)

2.5 Advanced Stop Line (ASL)

Advanced stop line (VirRoads, 2000; TfL, 2005; CROW, 2006) or forward stop bar (City of Portland, 2010) is a designated bicycle stop line ahead of adjoining motor vehicle stop lines with a lead in bicycle lane to give an early start to bicycles by separated stop line and simultaneous green light for all traffics. (Figure 4)

2.6 Bicycle Box

Bicycle box is a designated stacking area at the head of traffic lane at signalized intersection that requires vehicles to stop a short distance before the crosswalk allowing bicycles to stop in the area between the vehicles and the crosswalk by distancing vehicle stop line behind bicycle stop line and extending the stacking lane across the full width of the adjoining vehicle lane (VicRoads, 2000; CROW, 2006; City of Portland 2010; NACTO 2012). (Figure 5)

Figure 3. Bicycle signal (NACTO, 2012)

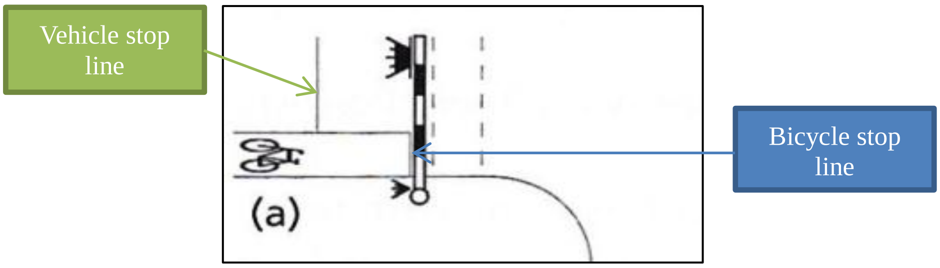

Figure 4. Advanced stop lines (CROW,2006)

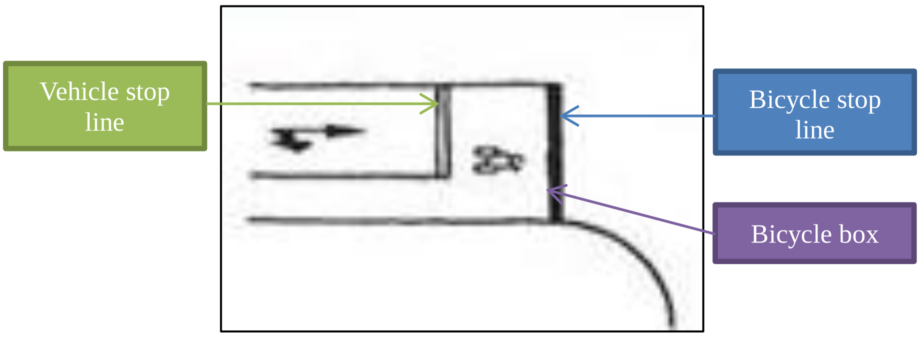

Figure 5. Bicycle box (CROW,2006)

2.7 Selection of Signalized Intersection Patterns

From the various signalized intersection designs described, five patterns were selected to be examined in this study with the following reasons: (1) Mixed traffic with left-turning motorist represents the current situation in Japan requiring vehicles to drive as nearest as possible to the left curb in the bicycle lane before turning (MLIT and NPA, 2012), though bicycle lanes were altered into suggestion lanes indicating mixing zones increasing awareness of motorists and bicyclists towards each other as a safety measure; (2) Left-turn in the intersection for represents situations where vehicles are not able to comply to the turning requirements resulting vehicles to turn in the intersection instead; (3) Bicycle signal, (4) Advanced stop lines and (5) Bicycle box are safety measures that implements early starts to increase bicycle safety examined in (2) Left-turn in the intersection situations (Table 1). The condition of each experimented intersection pattern selected is summarized in Table 2.

Vehicles and/or bicycle weaving (2.3 Weaving of Bicycles and/or Vehicles) designs were not examined because exclusive left-turn vehicle are necessary at the designed signalized intersections, therefore it is not appropriate to be examined and compared to designs without exclusive left-turn vehicle lanes at the signalized intersection examined in this study.

Table 1. Reasons for pattern selection

Pattern	Reason
(1) Mixed traffic with left-turning motorist	Current vehicle left-turn requirement with suggestion bicycle lanes instead of bicycle lanes as safety measure
(2) Left-turn in the intersection for motorist	Possible vehicle left-turn situations when motorists unable to comply turning requirements
(3) Bicycle signal	Separated traffic signal as safety measure during (2) Left-turn in the intersection for motorist situations (Early start pattern)
(4) Advanced stop lines	Advanced stop lines as safety measure during (2) Left-turn in the intersection for motorist situations (Early start pattern)
(5) Bicycle box	Bicycle box as safety measure during (2) Left-turn in the intersection for motorist situations (Early start pattern)

Table 2. Condition of experimented intersection patterns

Pattern	Position of stop line	Width of stop line	Traffic signal	Merging with vehicle traffic
(1) Mixed traffic with left-turning motorist	Same as vehicle	Width of road	Shared	Yes
(2) Left-turn in the intersection for motorist	Same as vehicle	Width of bicycle lane	Shared	No
(3) Bicycle signal	Same as vehicle	Width of bicycle lane	Separated	No
(4) Advanced stop lines	Ahead of vehicle	Width of bicycle lane	Shared	No
(5) Bicycle box	Ahead of vehicle	Width of road	Shared	No

3. RESEARCH METHODOLOGY

3.1 METHODOLOGY

The selected five patterns were prepared at the experiment site and the free simulation experiment was conducted. The experiment was conducted on 13 February 2012 at Saitama Prefecture Police driving practice facility or former Futatsunomiya driving license test site located in Nishi Ward, Saitama City, Saitama Prefecture, Japan.

14 human subjects were involved, 10 cyclists (9 males and 1 female) and 4 motorists (all males) driving 3 passenger cars and 1 truck. All human subjects are university students. The human subjects were travelled on the specified route freely. From the specified route, the situation of straight through bicycles and left-turn vehicles at the signalized intersection was created. (Figure 6)

After travelling on each pattern and after the experiment overall, the safety and comfort of the travelled patterns were surveyed through questionnaire surveys on the human subjects. The travelling conditions of the human subjects were recorded by video. In addition, an eye mark recorder (EMR-7 by NAC Image Technology) was installed on one human subject driving a passenger car was also recorded.

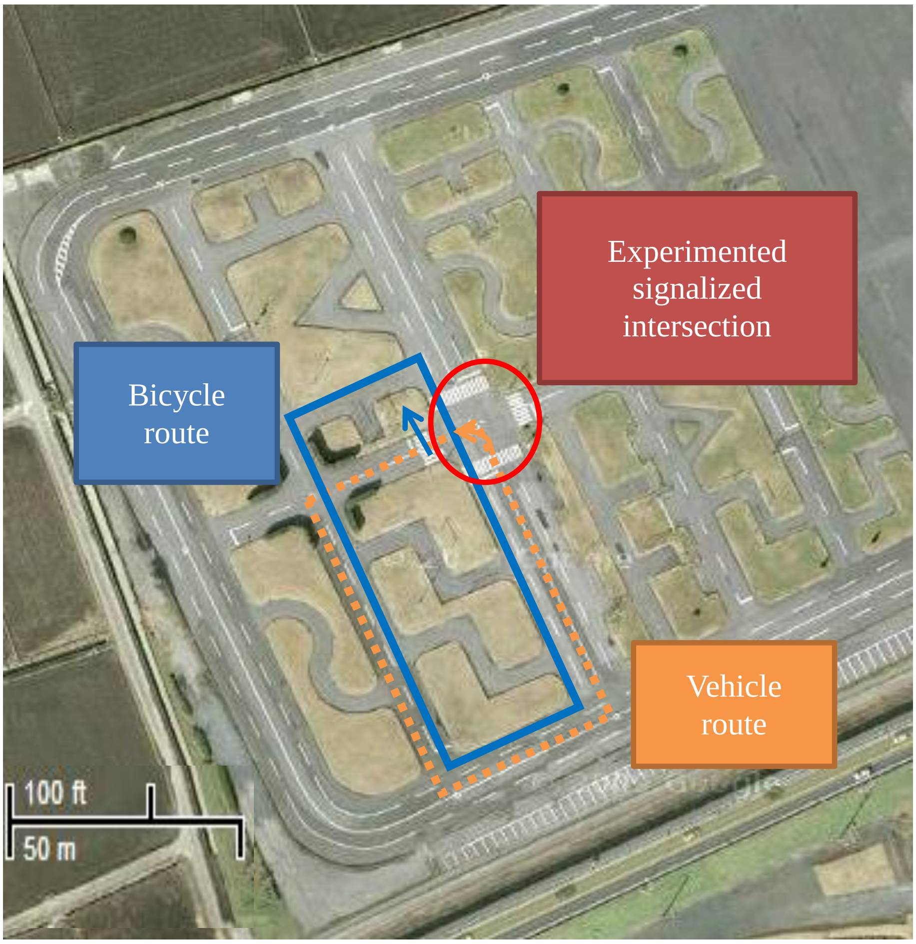

Figure 6. Specified bicycle and vehicle route at experiment site

3.2 Pattern Characteristics and Dimensions

Appropriate bicycle lane, vehicle lane and stop lines for each pattern was prepared at the experiment site (Table 3). Yellow markings were used to prohibit vehicles from entering the bicycle lanes while dashed white markings were used to indicate suggestion lane allowing vehicles entering the bicycle lanes. The original traffic signal, pedestrian crossings and dimensions of the signalized intersection were kept. No bicycle symbols and direction markings were prepared.

During the experiment, bicycle symbols were attached to the lights of a small scale traffic signal modifying the small scale traffic signal into a bicycle signal and positioned on the left side of the specified road. (Figure 7)

Table 3. Design characteristics and dimensions of all patterns

Patterns	Design characteristics	Dimensions
(1) Mixed traffic with left-turning motorist	Yellow markings ended 30 meters before stop line and continued by 5 meters dashed white markings until stop line	Figure 8
(2) Left-turn in the intersection for motorist	Yellow markings continued until stop line	Figure 9
(3) Bicycle signal	• Yellow markings continued until stop line • Bicycle signal positioned at the left side of the road before the intersection	Figure 10
(4) Advanced stop lines	• Vehicle stop line 5 meters behind bicycle stop line • Yellow markings continued until bicycle stop line	Figure 11
(5) Bicycle box	• Vehicle stop line 5 meters behind bicycle stop line • Bicycle stop line extended until end of vehicle lane • Yellow markings continued until vehicle stop line	Figure 12

Figure 7. “Bicycle signal” modified from small scale traffic signal

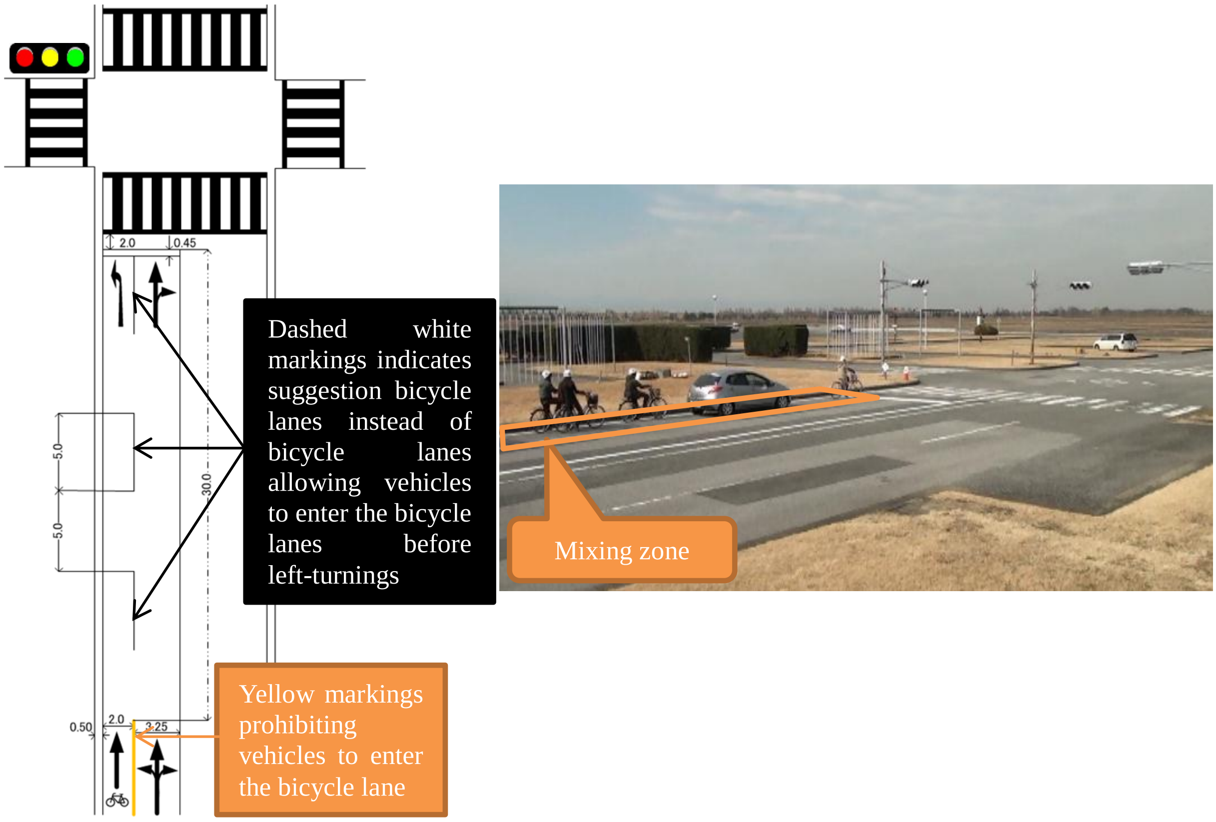

Figure 8. Mixed traffic with left-turning motorist

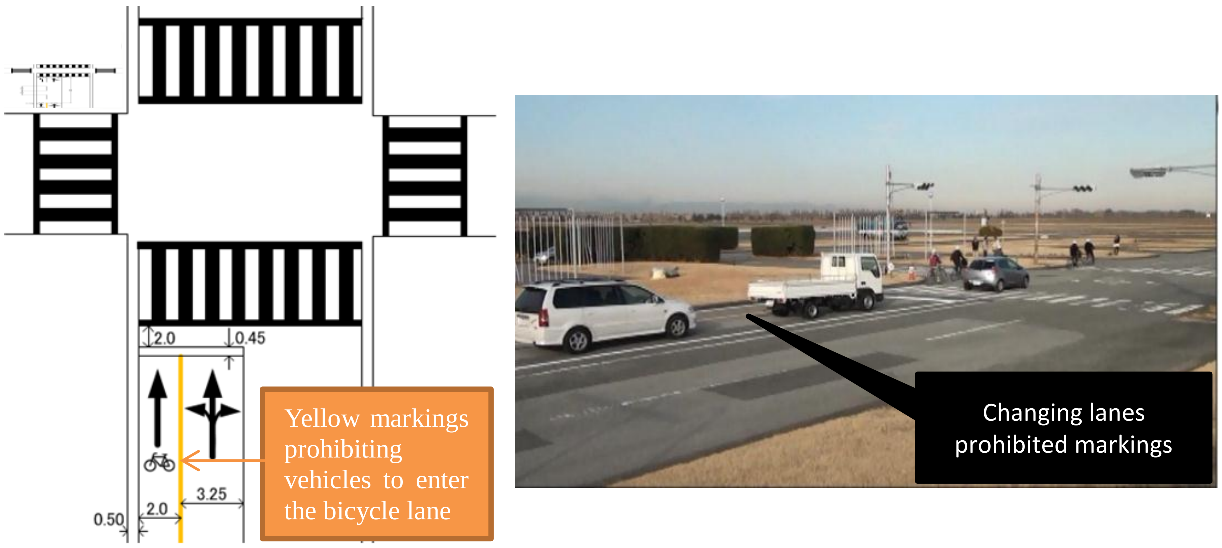

Figure 9. Left-turn in the intersection for motorist

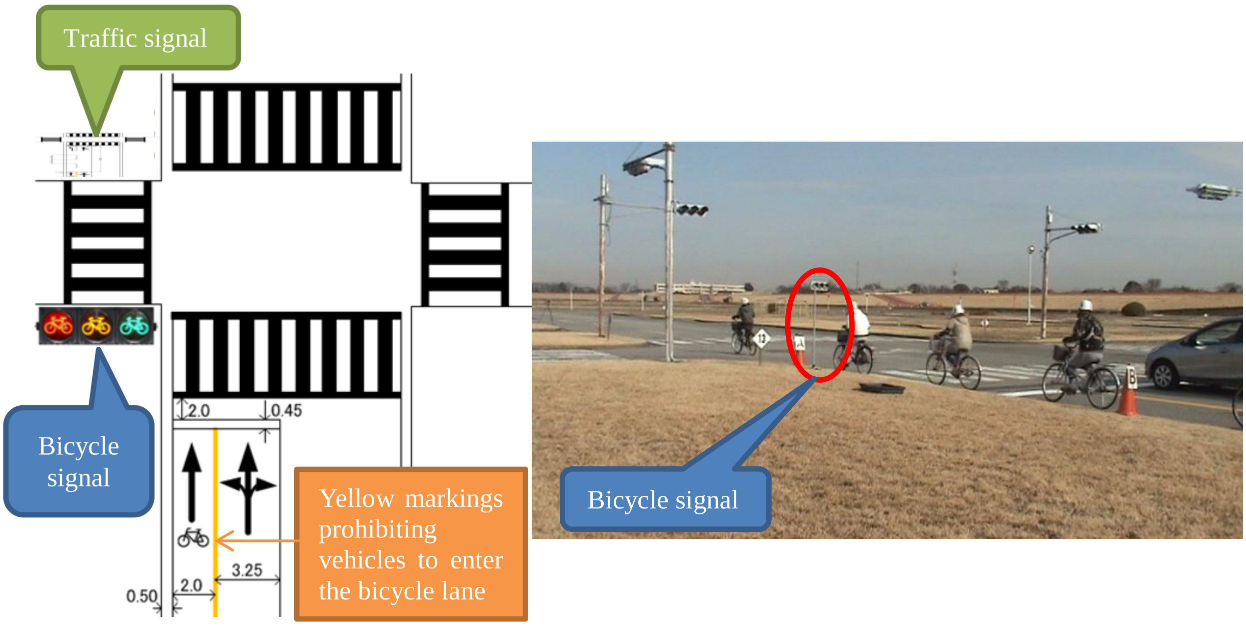

Figure 10. Bicycle signal

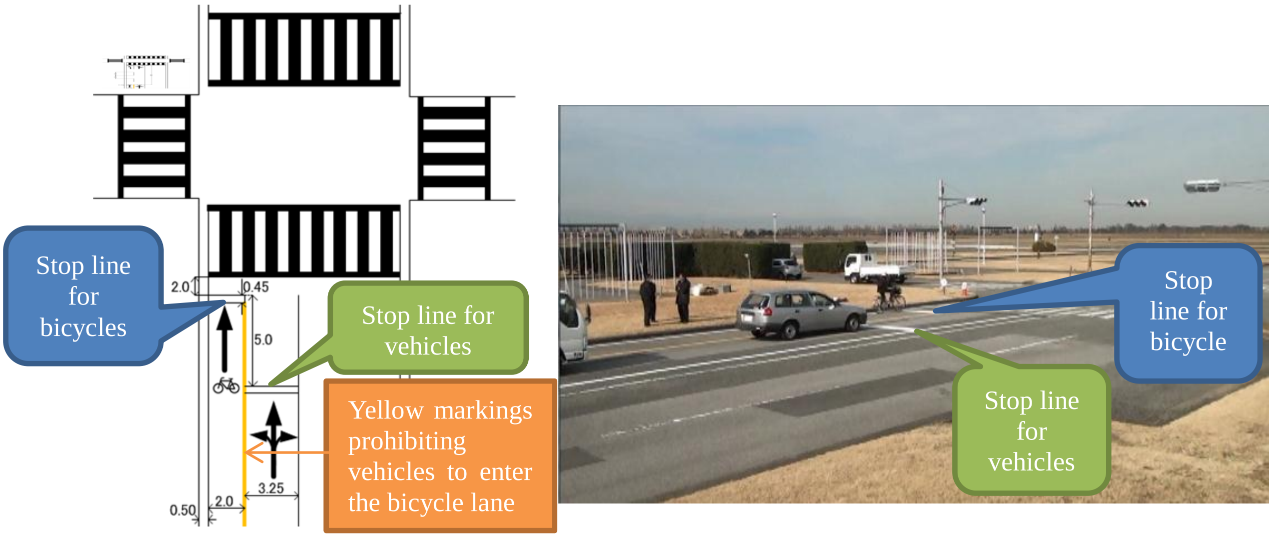

Figure 11. Advanced stop lines

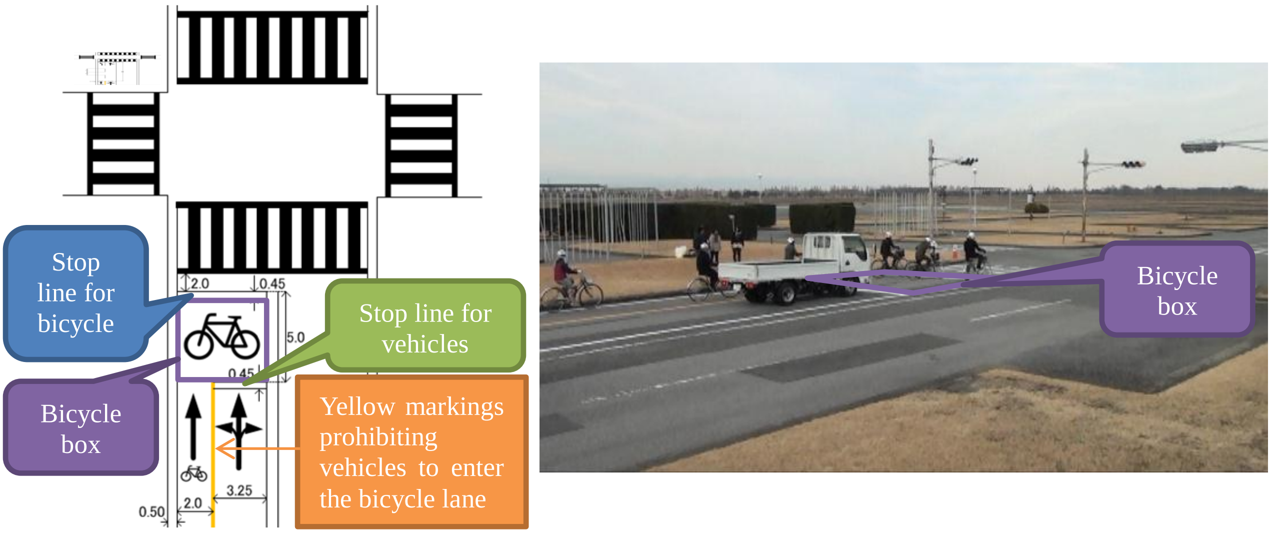

Figure 12. Bicycle box

4. RESULTS

In this section, the results from the following four analyses will be described: (1) Analysis on frequency of conflict points and near conflicts from video observation, (2) Analysis on blind spots and visibility of vehicles on the bicycles from the eye mark recorder recorded video, (3) Analysis on pattern preferences from questionnaire surveys, (4) Analysis on reason for pattern preferences from questionnaire surveys.

4.1 Analyses from Video Observations

4.1.1 Frequency of Conflict Points and Near Conflicts

Table 4 shows the results analyzed from the video observation collected throughout the experiment. From the video, the green signal time of traffic signal (GT) was counted and the number of bicycles intersecting with the vehicles was counted as the number of conflict points (CP). From CP, the number of sudden stops or sudden changes of directions by either bicycles or vehicles were counted as near conflicts (NC). Then the frequency of conflict points (CP/GT) and near conflicts (NC/CP) was calculated.

The results of frequency of conflict points (CP/GT) suggest that (1) Mixed traffic with left-turning motorist is the safest pattern (0.07) while (2) Left-turn in the intersection for motorist is the least safe pattern (17.16). (3) Bicycle signal is the second safest pattern having around one fifth (3.83) of the frequency occurred in (2) Left-turn in the intersection for motorist. Meanwhile (4) Advanced stop lines (9.52) and (5) Bicycle box (8.42) has around half (9.52) of the frequency occurred in (2) Left-turn in the intersection for motorist. On the other hand, the results of the frequency of near conflicts (NC/CP) suggest that (5) Bicycle box is the safest pattern (0.14) with (4) Advanced stop line near (0.15). On the other hand, (1) Mixed traffic with left-turning motorist is the least safe pattern (1.00)

Figure 13. Condition of video observation

Table 4. Frequency of conflict points (CP/GT) and near conflicts (NC/CP)

Pattern	Vehicle green light time, GT (min)	Conflict points, CP	CP/GT	Near conflicts, NC	NC/CP
(1) Mixed traffic with left-turning motorist	13.77	1	0.07	1	1.00
(2) Left-turn in the intersection for motorist	8.33	143	17.16	41	0.29
(3) Bicycle signal	29.51	113	3.83	29	0.26
(4) Advanced stop lines	16.39	156	9.52	23	0.15
(5) Bicycle box	16.39	138	8.42	19	0.14

4.1.2 Blind Spots and Visibility of Vehicles on Bicycles

Table 5 shows the result analyzed from the installed eye mark recorder video recorded. From the recorded video, the number of bicycles entered the intersection in the video was counted as the number of bicycles entered the intersection (N). From N, the number of bicycles entered the video from a blind spot was counted as the number of bicycles entered the intersection from blind spot (BS) while the number of bicycles not gazed by the driver before crossing the intersection was counted as the number of bicycles not gazed by the driver before bicycle crosses the intersection (NG). Then the frequency of BS and NG was calculated.

The results of frequency of BS (BS/N) suggest (1) Mixed traffic with left-turning motorist is the safest pattern (0.00) followed by (5) Bicycle box (0.22) and the other three patterns are almost the same to each other ((2) Left-turn in the intersection for motorist 0.33; (3) Bicycle signal 0.34; (4) Advanced stop lines 0.31). From the frequency of NG (NG/N), it is also suggested that (1) Mixed traffic with left-turning motorist is the safest pattern (0.00) and other four patterns are almost the same to each other.

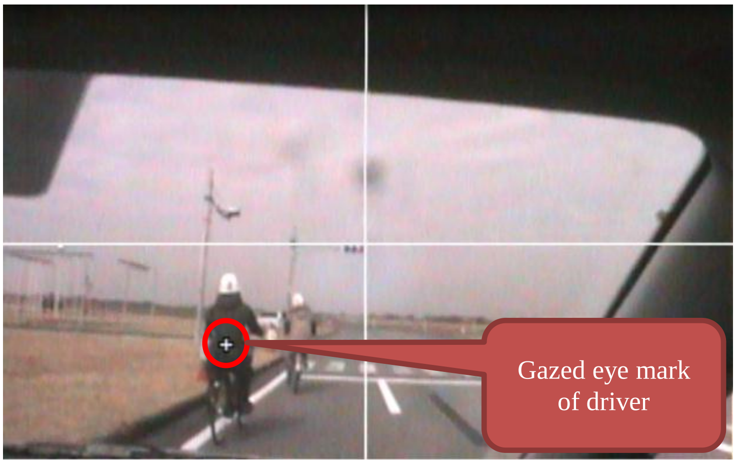

Figure 14. Recorded visibility and eye mark from eye mark recorder

Table 5. Results of bicycles entering from blind spots and not gazed by the driver

Pattern	No. of bicycles entered the intersection, N	No. of bicycles entered the intersection from blind spots, BS	BS/N	No. of bicycles not gazed by the driver before bicycle crosses the intersection, NG	NG/N
(1) Mixed traffic with left-turning motorist	25	0	0.00	0	0.00
(2) Left-turn in the intersection for motorist	89	29	0.33	50	0.56
(3) Bicycle signal	110	37	0.34	66	0.60
(4) Advanced stop lines	70	22	0.31	41	0.59
(5) Bicycle box	50	11	0.22	26	0.52

4.2 Analyses from Questionnaire Surveys

4.2.1 Pattern Preferences of Users

Table 6 shows the pattern preferences of bicyclist and motorist answered after travelling all five patterns (ranking from 1 to 5, with 1 being the most preferred). The results suggest that (1) Mixed traffic with left-turning motorist is preferred the most by motorists being preferred more as the second preferred pattern (2 persons) after being equally preferred as the first preferred pattern (1 person) with all other patterns besides (4) Advanced stop line while (3) Bicycle signal is preferred the least by motorists preferred as the fifth preferred pattern the most (2 persons). On the other hand, the results suggest that (3) Bicycle signal is preferred the most by bicyclists from being preferred more as the third preferred pattern (4 persons) than (5) Bicycle box (2 persons) after being equally preferred as the first preferred pattern (3 persons) and second preferred pattern (1 person) with (5) Bicycle box while (1) Mixed traffic with left-turning motorist is preferred the least by bicyclists preferred as the fifth pattern the most (5 persons).

Table 6. Pattern preferences of users

User	Pattern	Preferred pattern (person)				
		First	Second	Third	Forth	Fifth
Motorists	(1) Mixed traffic with left-turning motorist	1	2	0	0	1
	(2) Left-turn in the intersection for motorist	1	0	3	0	0
	(3) Bicycle signal	1	0	0	1	2
	(4) Advanced stop lines	1	1	0	1	1
	(5) Bicycle box	0	1	1	2	0
Bicyclists	(1) Mixed traffic with left-turning motorist	1	1	1	2	5
	(2) Left-turn in the intersection for motorist	2	3	0	2	3
	(3) Bicycle signal	3	1	4	2	0
	(4) Advanced stop lines	1	4	3	2	0
	(5) Bicycle box	3	1	2	2	2

4.2.2 Reasons of Pattern Preferences of Users

Table 7 shows the summarized responses of motorists on the different intersection patterns answered after travelling on the intersection. The results indicate that more than half of the motorists (2 persons or more) agreed that (1) Mixed traffic with left-turning motorist was easy to turn in all conditions. In addition, no motorists agreed on that the bicycles was prioritized more than the vehicles overall for that particular pattern.

Table 8 shows the summarized responses of bicyclists on the different intersection patterns answered after travelling on the intersection. The results suggest that bicyclists did not felt safe in (1) Mixed traffic with left-turning motorist where more than half of bicyclist (5 persons or more) answered it was not safe in all conditions questioned. Instead, bicyclists had a hard time looking at the separated signals in (3) Bicycle signal, where half of the bicyclists (5 persons) had mistakenly looked at the wrong signal. On the other hand, bicyclists did not feel safe from the separated stop lines in (4) Advanced stop lines, where some bicyclists did not felt safe stopping during red light (3 persons) and when the traffic signal became green in a leading position (2 persons). Meanwhile, more bicyclists felt unsafe from the extended stacking area of (5) Bicycle box where more bicyclists did not felt safe stopping during red light (5 persons) and when the traffic signal became green in a leading position (5 persons).

Table 7. Summarized responses of motorists on the different patterns

Pattern	Question	Response (person)		
		Agree	Neither	Disagree
(1) Mixed traffic with left-turning motorist	When traffic signal became green (leading position): It was easy to turn	3	1	0
	When traffic signal became green (not leading position): It was easy to turn	2	1	1
	When turning at the signalized intersection without stopping (leading position): It was easy to turn	2	1	1
	When turning at the signalized intersection without stopping (not leading position): It was easy to turn	2	2	0
	Overall, bicycles was prioritized more than vehicles	0	0	4

Table 8. Summarized responses of bicyclists on the different patterns

Pattern	Question	Response (person)		
		Agree	Neither	Disagree
(1) Mixed traffic with left-turning motorist	When stopping during red light: It was safe	1	2	7
	When traffic signal became green (leading position): It was safe	4	0	6
	When traffic signal became green (not leading position): It was safe	2	1	7
	When crossing the intersection without stopping (leading position): It was safe	3	2	5
	When crossing the intersection without stopping (not leading position): It was safe	1	2	7
(3) Bicycle signal	Mistaken at separated signals	5	3	2
(4) Advanced stop lines	When stopping during red light: It was safe	7	0	3
	When traffic signal became green (leading position): It was safe*	6	0	2
(5) Bicycle box	When stopping during red light: It was safe	3	2	5
	When traffic signal became green (leading position): It was safe	4	1	5

- * The total bicyclists do not add up to 10 persons because 2 bicyclists did not face the leading position during traffic signal became green situation.

Table 9 shows the summarized reasons on each responses answered by the bicyclists. The results suggest that bicyclists did not felt safe when stopping at red light in (1) Mixed traffic with left-turning motorist was not because the traffic was mixed (1 person), but it was not safe because there were vehicles positioned in front (3 persons) and behind (2 persons) of the bicyclists. (4) Advanced stop lines because the vehicles were positioned behind (3 persons) instead of difficult to be seen (1 person). More bicyclists felt the same for (5) Bicycle box where bicyclists reasoned that (5) Bicycle box was not safe because the vehicles were positioned behind (5 persons) instead of difficult to be seen (1 person). Contrary, bicyclists did not felt safe when the traffic signal turned into green in a leading position because the vehicles were difficult to be seen (5 persons) instead of vehicles were positioned behind (1 person).

Table 9. Summarized reasons for the responses of bicyclists

Pattern situation	Reason	Select count (person)
(1) Mixed traffic with left-turning motorist was not safe when stopping at red light	Because the traffic was mixed	1
	Because vehicles were positioned in front	3
	Because vehicles were positioned behind	2
(4) Advanced stop lines was not safe when stopping at red light	Because vehicles were positioned behind	3
	Because vehicles were difficult to be seen	1
(5) Bicycle box was not safe when stopping at red light	Because vehicles were positioned behind	5
	Because vehicles were difficult to be seen	1
(5) Bicycle box was not safe when the traffic signal turned into green in a leading position	Because vehicles were positioned behind	1
	Because vehicles were difficult to be seen	5

5. DISCUSSIONS

This study investigated the safety measures from various signalized intersection designs with bicycle lanes from bicycling developed countries or areas. Then the feasible signalized intersection patterns were determined by comparing both safety and comfort of the design while focusing on left-hook accidents by executing a free simulation experiment. This study compared the effectiveness of various intersection designs with bicycle lanes from the perspective of safety and comfort. From this study, early starts and mixed traffic are the safety measures available from the various signalized intersection designs. From the signalized intersection patterns experimented, (1) Mixed traffic with left-turning motorist is the safest signalized intersection design while (3) Bicycle signal is the most comfortable pattern for bicyclists.

(1) Mixed traffic with left-turning motorist is the safest pattern from the video observation though it is the most uncomfortable pattern from user perspective. By positioning bicycles and vehicles in front or behind of each other before entering the intersection, there was no possibility for conflict points to occur since bicycles and left-turning vehicles enter the intersection without intersecting each other. Furthermore, the visibility of bicycles from vehicles and bicycles gazed by vehicle driver was improved by the positioning of bicycles in front of vehicles. From these results, it is proved that (1) Mixed traffic with left-turning motorist can reduce left-hook accident situations, increase visibility of bicycles from vehicles and reduced looked-but-failed-to-see accidents. These results are supported by the fact that (1) Mixed traffic with left-turning motorist reduces left-hook accidents at intersections (NACTO, 2012). Though, this pattern has a high frequency of near conflict that is because when a bicycle travels on the left side of the vehicles by force, the bicycle will enter the intersection from a blind side unexpectedly, causing conflicts or particularly left-hook conflicts to occur. Thus, it is important for vehicles to travel as near as possible to the left curb not allowing bicycles to travel through the left side of vehicles causing unexpected conflict situations. While being safe, this pattern is also convenient for left-turning motorist shown from being the most preferred pattern by motorists while also being agreed that this pattern can be easily turned by left-turning motorist in all conditions. On the other hand, (1) Mixed traffic with left-turning motorist was not comfortable for bicyclists from the fact the bicyclists did not felt

safe in all conditions. Though, the reason was not because the traffic was mixed with vehicles, but because the vehicles were positioned in front and behind of the bicyclists. More bicyclists reasoned by having vehicles in front was less safe than having vehicles behind suggesting that bicyclists was affected by the exhaust fumes. The results of (1) Mixed traffic with left-turning motorist supports the fact that there are contradictions between the requirements of safety and comfort to have quality bicycle facilities (PRESTO, 2010).

(2) Left-turn in the intersection for motorist is the least safe pattern from the video observation. The reason is because bicycles were positioned on the left hand side of vehicles in bicycle lanes creating a situation where left-turn vehicles need to intersect with through bicycles before turning. By implementing early start safety measures into this pattern, the frequency of conflict points can be reduced as suggested (CROW, 2006). However, early start safety measures are only applicable during bicycle departures when green traffic signal or green bicycle signal was given while there were no implications on other conditions besides early stops by (3) Bicycle signal. On the other hand, this pattern has a higher number of gazed bicycles than early start patterns besides bicycle box. The possible reason is there is a possibility that the driver unconsciously did not look at the waiting bicycles located at the left side of the driver because it was unnecessary to look at the bicycles since the bicycles are going to cross the intersection before the driver enters the intersection. Instead, (5) Bicycle box has a higher number of gazed bicycles because the bicycles are positioned in front of the driver causing the driver the unconsciously gazed at the bicycles although unnecessary. This suggests that there is a possibility for drivers not looking or searching for bicycles when early starts are given to bicycles, often done by drivers developing visual scanning strategies based on the frequency of dangerous events only in a certain situation (Summala *et al.*, 1996).

(3) Bicycle signal is both safe from the video observation and the most comfortable pattern from user perspective. This pattern has a lower possibility of conflict points than other early start patterns since (3) Bicycle signal are also able to reduce conflict points during bicycle departures and before red traffic signals from early starts and early stops while other early start patterns are only able to reduce conflict point during bicycle departures. This increases the safety of this pattern than other early start patterns that can be seen from the higher decrease in frequency of conflict points in this pattern than the other early start patterns. Early stop is also important to give vehicle sufficient turning time on two phase signalized intersection without obstruction from through bicycles (Pan and Cheng, 2011). Insufficient turning time may cause vehicles to turn in a rush since the traffic signal is already red causing improper turnings resulting into left-hook collisions. Though, in this pattern, bicyclist mistakenly looked at the separated signals. The possible reason for this incident to occur is because the low visibility and inadequate position of bicycle signal. In this study, the bicycle signal used was not a bicycle signal originally, but it was a modified traffic signal using cardboards to indicate bicycle signal symbol that may reduce the visibility of the "bicycle signal" than the original bicycle signal. It is suggested that bicycle signal should be located at the far-side of intersections with additional near-side bicycle signals supplementing the far-side bicycle signal (NACTO, 2012). However, the bicycle signal is positioned only on the near-side of the travelled route because of the low visibility of the "bicycle signal" and the availability of the "bicycle signal" (one available). Nevertheless, (3) Bicycle signal is preferred more than other patterns suggesting that (3) Bicycle signal is an appropriate or comfortable pattern from user perspective.

(4) Advanced stop lines is a safe pattern from the video observation though not a comfortable pattern from user perspective. From the positioning of bicycle stop line in front of vehicle stop line as early start safety measures, the frequency of conflict points and near conflicts is reduced increasing the safety of the intersection. Meanwhile, the number of

bicycles entered the visibility of driver from blind spots is also reduced. Though, with the separated stop line, the bicyclists felt unsafe during red traffic signals from the positioning of vehicles behind the bicycles. This suggests that some bicyclists were worried for not being able to look at vehicles during red signal creating an uncomfortable situation for bicyclists.

(5) Bicycle box is a safer pattern than (4) Advanced stop lines while also a more uncomfortable pattern than (4) Advanced stop lines. The safety of (5) Bicycle box is increased by the expanded stacking spaces by positioning more bicycles in front of vehicles than (4) Advanced stop lines. However, the expanded stacking spaces also causes (5) Bicycle box to be more uncomfortable for bicyclists than (4) Advanced stop lines from the increasing number of bicyclists felt unsafe with during red traffic signals. In addition, the expanded stacking spaces positions bicycles right in front vehicles causes the bicyclists to feel unsafe during traffic signals became green from the difficulty to see the vehicles that were positioned behind them suggesting that the bicyclists were worried about the movement of the vehicles behind them. Nevertheless, (5) Bicycle box is a pattern designed to ease right-turn bicyclist by positioning bicycles on the right side of the bicycle stacking area during red traffic signal (Transport for London, 2005; CROW, 2006; NACTO, 2012). Bicycles in Japan are not allowed to have a direct right-turn at signalized intersection that may influence the perspective of the bicyclists on this matter.

There were some limitations in this study. The examined visibility and gazed bicycles from the driver could not represent our human eyes adequately. The recorded video by the eye mark recorder used in this study, EMR-7 by NAC Image Technology had only 60 degrees view area though the human eyes have a higher view area than that degree. All human subjects in this study are university students not representing other road users especially the elderly and children. Moreover, the four human subjects representing the motorists are only a small sample. The traffic condition in this study does not represent several traffic conditions including traffic with higher proportion of motorists, congested traffic and peak hour traffic situations. Further study needs to explore the implications of other various traffic conditions on the different bicycle safety measures to further assist in developing more specific solutions to increase cyclist safety at signalized intersections. Lastly, the motorists are well known about the presence of bicyclists going through the intersection which may cause them to be more aware than normal driving situations.

Nevertheless, the results are consistent with previous studies where cyclists prefer to be separated rather than sharing the road with motorists (Bohle, 2000; Stinson and Baht, 2003; Tilahun *et al*, 2007; Haworth and Schramm, 2011; Caulfield *et al*, 2012); and cyclists showing a positive response towards the bicycle safety measures installed for (4) Advanced stop lines for bicycles (Newman *et al*, 2002; Wall *et al*, 2003; Allen *et al*, 2005; Rodgers, 2005) and (5) Bicycle box (Newman *et al*, 2002; Rodgers, 2005; Dill *et al*, 2012), favoring (4) Advanced stop lines for bicycles over (5) Bicycle box (Newman *et al*, 2002). Though, comparisons cannot be made regarding (3) Bicycle signal due to the very little in terms of published literature related (Thompson *et al*, 2013).

6. CONCLUSIONS

On the basis of the results of this study, it can be concluded that (3) Bicycle signal is the most comfortable pattern for bicyclists. (3) Bicycle signal is also the most preferred pattern from the preferences of the bicyclist. The bicyclists did not agree that (4) Advanced stop lines and (5) Bicycle box is safe because vehicle movements cannot be seen since the vehicles were positioned behind the bicyclists. From the video analysis, the reduced left hooks of (3) Bicycle signal is the highest between early start patterns ((3) Bicycle signal, (4) Advanced stop lines, (5) Bicycle box). Therefore, (3) Bicycle signal is also effective in terms of safety.

On the other hand, bicyclists did not agree that (1) Mixed traffic with left-turning motorist is a safe pattern. Though, from the video analysis, (1) Mixed traffic with left-turning motorist had the ability to reduce left hooks higher than other patterns by preventing bicycles from entering the intersection from a blind spot and increasing the numbers of bicycles gazed by the vehicles before turning. Therefore, (1) Mixed traffic with left-turning motorist is the most valid pattern in term of safety.

ACKNOWLEDGEMENTS

The authors wish to thank Saitama Prefecture Police Department for their various supports.

REFERENCES

AASHTO (2012) Guide for the Development of Bicycle Facilities. Fourth Edition. American Association of State Highway and Transportation Officials.

Allen, D., Bygrave, S., Harper, H. (2005) Behaviour at cycle advanced stop lines. Published project report. Transport Research Laboratory, London, England.

Aultman-Hall, L., Adams, M., F. (1998) Sidewalk bicycling safety issues. *Transportation Research Record: Journal of the Transportation Research Board*, 1636(-1), 71-76.

Bohle, W. (2000) Attractiveness of bicycle-facilities for the users and evaluation of measures for the cycle-traffic. In Traffic Safety on Two Continents Conference, 89-94.

Caltrans (2006) Highway Design Manual, Chapter 1000 Bicycle Transportation Design. California Department of Transportation

Caulfield, B., Brick, E., McCarthy, O., T. (2012) Determining bicycle infrastructure preferences–A case study of Dublin. *Transportation research part D: transport and environment*, 17(5), 413-417.

City of Portland (2010) Portland Bikeway Facility Design, Survey of best practices.

Constant, A., Lagarde, E. (2010) Protecting Vulnerable Road Users from Injury. *PLoS Med* 7(3): e1000228, 2010.

CROW (2006) Design Manual for Bicycle Traffic. The Netherlands.

Dill, J., Carr, T. (2003) Bicycle commuting and facilities in major US cities: if you build them, commuters will use them. *Transportation Research Record: Journal of the Transportation Research Board*, 1828(-1), 116-123.

Dill, J., Monsere, C., M., McNeil, N. (2012). Evaluation of bike boxes at signalized intersections. *Accident Analysis & Prevention*, 44(1), 126-134.

Kane County (2012) Kane County Bicycle and Pedestrian Plan. Forest Preserve District of Kane County, Kane County, Kane/Kendall Council of Mayors.

FHWA (2009) Manual of Uniform Traffic Control Devices for Street and Highways 2009 Edition. U.S. Department of Transportation, Federal Highway Administration.

Haworth, N., Schramm, A. (2011) How do level of experience, purpose for riding, and preference for facilities affect location of riding?. *Transportation Research Record: Journal of the Transportation Research Board*, 2247(1), 17-23.

Herslund, M., B., Jørgensen, N., O. (2003) Looked-but-failed-to-see-errors in traffic. *Accident Analysis & Prevention*, 35(6), 885-891.

Hunter, W., W. (2000) Evaluation of a combined bicycle lane/right turn lane in Eugene, Oregon (No. FHWA-RD-00-151,).

JAMA(2009) Safe Roads and Increasing Awareness for Safe Bicycle Coexistence. Japan Automobile Manufacturers Association. (In Japanese)

Johnson, R. (2011) Bicycle-friendly city hooked on dangerous intersections. Columbia Daily Tribune.

Kim, K., & Li, L. (1996) Modeling fault among bicyclists and drivers involved in collisions in Hawaii, 1986-1991. *Transportation Research Record: Journal of the Transportation Research Board*, 1538(-1), 75-80.

MILT (2010) Bicycle Development Status. Ministry of Land, Infrastructure, Transport and Tourism (In Japanese)

MILT (2011) Bicycle Development Status. Ministry of Land, Infrastructure, Transport and Tourism (In Japanese)

MILT, NPA (2012) Guideline for Safe and Comfortable Cyclist Environment. Road Bureau of Ministry of Land, Infrastructure, Transport and Tourism; Traffic Bureau of National Police Agency. (In Japanese)

NACTO (2012) Urban Design Guide. National Association of City Transport Officials.

Newman, A., Cycle Planning Officer, City Streets Unit, Christchurch City Council (2002) The marking of advanced cycle lanes and advanced stop boxes at signalised intersections. City Streets Unit, Christchurch City Council, Christchurch, New Zealand.

Pan, T., Cheng, L. (2011) Study of Signal Control Based on Conflicts between Right-Turn Vehicles and Straight-Going Bicycles. In 11th International Conference of Chinese Transportation Professionals (ICCTP).

Portland Bicycle Plan for 2030 (2010) Bikeway Facility Design: Survey of Best Practices, 2010. City of Portland Bureau of Transportation.

PRESTO (2010) PRESTO Cycling Policy Guide, Cycling Infrastructure.

Reynolds, C., C., Harris, M., A., Teschke, K., Cripton, P., A., Winters, M. (2009) The Impact of Transportation Infrastructure on Bicycling Injuries and Crashes: A Review of the Literature. *Environmental Health 8 (1), 47.*

Rodgers, A. (2005) A23 & A202 ASL Before and After Study. Transport for London, London.

Stinson, M., A., Bhat, C., R. (2003) Commuter bicyclist route choice: analysis using a stated preference survey. *Transportation Research Record: Journal of the Transportation Research Board*, 1828(1), 107-115.

Summala, H., Pasanen, E., Räsänen, M., Sievänen, J. (1996) Bicycle accidents and drivers' visual search at left and right turns. *Accident Analysis & Prevention*, 28(2), 147-153.

TfL (2005) London Cycling Design Standards. Transport for London.

Tilahun, N., Y., Levinson, D., M., Krizek, K., J. (2007) Trails, lanes, or traffic: Valuing bicycle facilities with an adaptive stated preference survey. *Transportation Research Part A: Policy and Practice*, 41(4), 287-301.

Thompson, S., R., Monsere, C., M., Figliozzi, M., Koonce, P., Obery, G. (2013) Bicycle-Specific Traffic Signals: Results from a State-of-the-Practice Review. In Transportation Research Board 92nd Annual Meeting (No. 13-0536).

VicRoads (2000) “Head start” Storage Areas at Intersection. Cycle Notes No.5 February 2000.

VicRoads (2001) Providing for Cyclists at Signalized Intersections. Cycle Notes No.8 February 2001.

Wachtel, A., Lewiston, D. (1994). Risk factors for bicycle-motor vehicle collisions at intersections. *Journal of ITE*, Vol. 64, No. 9, pp.30-35.

Wall, G., T., Davies, D., G., Crabtree, M. (2003) Capacity implications of Advanced Stop Lines for cyclists. Transport Research Laboratory.

Wang, Y., Nihan, N., L. (2004) Estimating the risk of collisions between bicycles and motor vehicles at signalized intersections. *Accident Analysis & Prevention*, 36(3), 313-321.