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ABSTRACT

With the increase of bicycle use, cycling safety and functions of bicycle facilities have attracted a lot of attention in recent years. In this study, by using data collected at four intersections, we provide some important insights into the operation of the bicycle lane in Japan. The findings show that, the bicycle lane directly linking to the crosswalk can be effectively used, but for cyclists the risk with motor vehicles simultaneously crossing the crosswalk is relatively higher, compared to the bicycle lane that directly connects the sidewalk corner at intersections. The sensitivity analysis of the proposed bicycle lane usage model reflects that reducing the entrance angle of the bicycle lane can improve the bicycle lane usage noticeably, and the desired value of entrance angle is less than 30 degrees. Besides, the subway entrance or the bus stop located near intersections makes most of cyclists change their paths, from the analysis on cyclists' path-changing behaviour.

Keywords: bicycle lane, bicycle lane usage, cycling safety, path-changing behaviour

INTRODUCTION

The bicycle use in the past decades has dramatically increased both in developed and developing countries and the increasing trend may last for a long time, due to the low energy consumption, health benefits and the low cost of the cycling trip (Allen et al. 1998, Wang et al. 2008). In Japan, with the total population of 120 million, the number of bicycles is up to 69 million in 2008 and the number has been increasing in recent years. Moreover, 20 percent of trips less than 5 km are made by the bicycle (National Police Agency.2012). Hence, cycling is an important urban transport mode for most Japanese citizens. With the popularity of bicycles, the research relating to cyclist behaviour and bicycle facilities have naturally attracted a lot of attention.

Using bicycle accident data, Stone and Broughton (2003) extracted and tabulated selected incidence and fatality rates of cycling accidents recorded by the police in Great Britain during 1990–1999, in a database of over 30,000 standardized reports of fatal or serious injury accidents. And, the concept of exposure invariance was developed to estimate the relative risk of different sorts of bicycle/vehicle encounter. Two models of perceived cycling risk and a model of acceptability have been proposed by Parkin et al. (2007), based on responses from a sample of 144 commuters to video clips of routes and intersections. Moreover, Toronto bicycle commuter safety rates were analyzed by Aultman-Hall and Kaltenecker (1999). Kim et al. (2007) explored the factors contributing to the injury severity of bicyclists in bicycle–motor vehicle accidents using a multinomial logit model. Allen et al. (1998) recommended procedures for the operational analysis of uninterrupted bicycle facilities. A stated preference experiment was performed in Edmonton in Canada to both examine the nature of various influences on bicycle use and obtain ratios among parameter values to be used in the development of a larger simulation of household travel behaviour (Hunt and Abraham 2007). Besides, recognizing that facility design plays a large role in encouraging (or discouraging) bicycling, Duthie et al. (2010) examined the impact of bicycle facility design on the behaviour and safety of bicyclists and motorists. The research by Landis et al. (2003) built on the Bicycle level-of-service methodology to address the level-of-service for bicycle through movements at signalized intersections. Krizeka and Roland (2005) provided better understanding for the severity of instances where separate on-street bicycle facilities end and corresponding physical characteristics, based on data measuring physical attributes of the selected sites and cyclists perceptions of the level of comfort. In order to separate motor vehicles from bicycles and to distribute the road resource reasonably between motor vehicles and bicycles, Wang et al. (2008) investigated the bicycle conversion factors.

While the cyclist-related researches have been widely conducted, the operation of the bicycle lane at intersections was rarely concerned. Besides, in Japan, cyclists are allowed to share vehicle lanes or sidewalks, even there exit bicycle lanes simultaneously. There are rising concerns over the influences of bicycles on drivers and pedestrians at intersections where conflicts between bicycles and left-turn vehicles often occur. Therefore, more and more Japanese researchers paid their attention to the operation and geometries for bicycle users in recent years. The objective of this study is to investigate the operation of bicycle lanes at intersections, as a case study in Japan. By using the data collected at four intersections with different bicycle lane designs, the bicycle lane usage, cycling safety and path-changing behaviour are thoroughly discussed. We believe that the findings in this research would be useful to researchers and practitioners working on the bicycle lane planning and design.

The paper is organized as follows: The introduction of study sites and data collection is in the subsequent section. Analysis on the bicycle lane usage, cycling safety and path-changing behaviour is given in section three through five. The last section is devoted to the conclusions.

STUDY SITES AND DATA COLLECTION

In this study, the selected intersections are situated in the downtown of Nagoya, Japan, with the different design of the bicycle lane. The designs of the selected intersections are shown in Figure 1, where bicycle lanes are painted red. In addition, Fushimi, Sakae3 and Mitsukura intersections are successively located on a main street of Nagoya. Since we focus on the operation of the bicycle lanes with different designs at intersections, only the bicycle lanes in the right side of each intersection are discussed in this study and the upstream and downstream of the intersections are denoted as A through H, for convenience. And, we mention that it is left-hand traffic in Japan.
The design of the bicycle lane at Fushimi intersection is the most common one in Japan. The bicycle lane is disrupted by the relatively prominent intersection. Cyclists and pedestrians share the sidewalk corners. Besides, there are two subway entrances near area A.

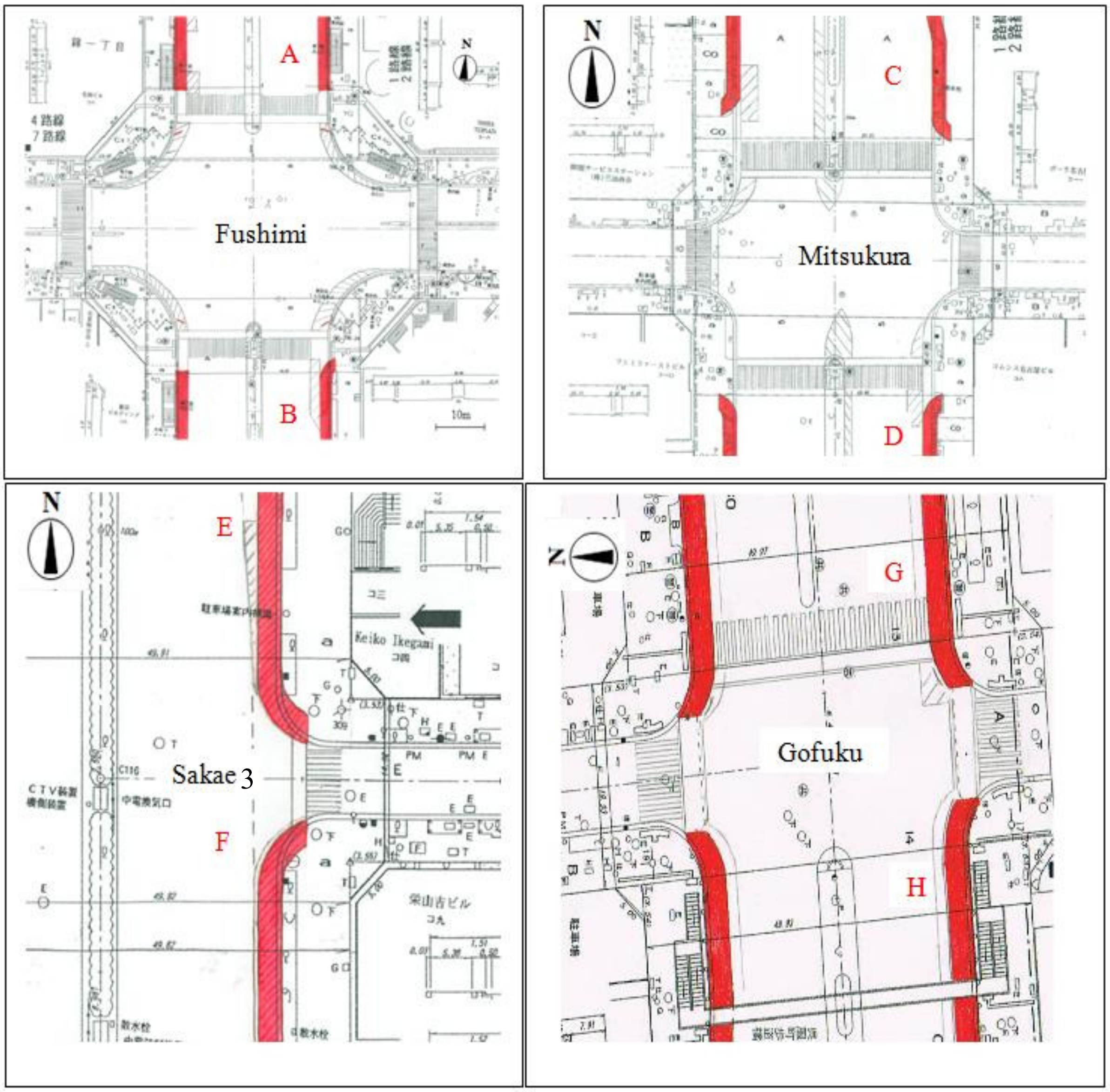

Figure 1 – The designs of the study intersections

Table 1 – The width of the bicycle lane and the sidewalk at each study area [unit: m]

	Fushimi		Mitsukura		Sakae 3		Gofuku	
	A	B	C	D	E	F	G	H
Bicycle lane	2.5	2.5	2.5	2.5	2.5	2.5	3.0	3.0
Sidewalk	3.3	4.4	4.0	5.7	4.4	4.4	3.5	3.5

The bicycle lane at Mitsukura intersection is similar with that at the Fushimi intersection, except a bus stop located in the area D and no subway entrances. At Sakae3 intersection, the bicycle lane is disrupted by a typical unsignalized T-intersection where the bicycle lane directly connects the crosswalk. The bicycle lane constructed at Gofuku intersection also links directly to the crosswalk, which makes it different from the bicycle lane at Fushimi and Mitsukura intersection.

For all considered intersections, in the crosswalks cyclists and pedestrians are separated by the bicycle markings and the bicycle lanes discussed in this study are physically protected by fences. The width of the bicycle lane and the sidewalk at each area is listed in Table 1.

The data used in this research were collected during the morning peak periods in two days, by several video cameras mounted on the nearby high story buildings and pedestrian overpasses. At Fushimi, Mitsukura and Sakae3 intersections, the data were simultaneously collected during 8:00 - 10:10 am, Oct. 20, 2009. Therefore, the cyclists riding from Fushimi to Mitsukura or in the opposite direction can be tracked. At Gofuku intersection, the data were collected during 8:00 - 10:10, Oct. 6, 2011.

ANALYSIS ON THE BICYCLE LANE USAGE

The design and construction of bicycle lane largely depend on the extent to which the bicycle lane will be effectively used. In order to offer some support for the future bicycle lane planning, in this section, first, we statically compare the bicycle lane usage in each discussed area. The bicycle lane usage is defined as the ratio of the number of cyclists using the bicycle lane to the total number of cyclists riding through the corresponding area. The comparison results are presented in Table 2.

Table 2 – The usage of the bicycle lane located in each area

	8:00 - 9:00		9:10 - 10:10	
Area	Number of cyclists	Bicycle lane usage [%]	Number of cyclists	Bicycle lane usage [%]
A	125	20.8	62	1.6
B	100	26.0	87	21.8
C	222	82.0	131	37.4
D	145	5.5	92	2.2
E	173	82.7	115	40.0
F	79	68.4	84	38.1
G	24	83.3	28	89.3
H	138	88.4	64	83.1

From Table 2, it is clear that, in relation to the usage of the bicycle lane in areas A, B and D, the usage of the bicycle lane in areas C, E and F is relatively higher, which may be caused by the larger number of pedestrians in the sidewalks from Fushimi direction. For Gofuku intersection, the bicycle lane is effectively used, with the usage more than 83%. The main reason for the high bicycle lane usage in areas G, H is considered to be the design that the bicycle lane directly connects the crosswalk. For cyclists, such design greatly facilitates avoiding conflicts with pedestrians and speed obstruction. In addition, the relatively broader width of the bicycle lane and the minor width difference between the bicycle lane and the sidewalk also contribute to the higher usage, to some extent.

Table 3 – The estimation results for the bicycle lane usage model

Explanatory variables	parameters
The angle from the sidewalk corner to the entrance of bicycle lane [radian]	-3.51*
The area of the sidewalk [m^2]	-0.02 *
The dummy variable for the presence of pedestrians or cyclists in the sidewalk corner	0.51 ***
The ratio of the number of pedestrians and cyclists near the entrance of bicycle lane to the total number of pedestrians and cyclists in the sidewalk corner	-1.24**
The dummy variable for the presence of opposite pedestrians or cyclists	0.53**
The ratio of the number of opposite cyclists to the total number of cyclists in the bicycle lane	-1.26**
Constant	6.14*
The percent correctly predicted [%]	77.23
Nagelkerke R-square	0.484
Number of samples	527

*,**and *** denote the significance of corresponding parameters at 1%, 5% and 10% confidence level respectively.

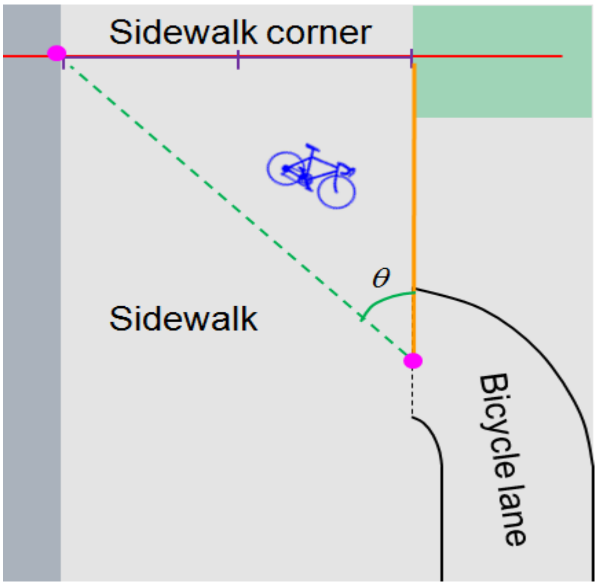

Figure 2 – The definition of the entrance angle θ of the bicycle lane

Table 4 – The sensitive analysis of the bicycle lane usage model

		Bicycle lane usage [%]		
		A	B	C
Observed usage		10.6	34.0	68.5
Predicted usage		7.0	32.0	64.9
The alternative geometry	Entrance angle less than 45 degrees	21.2	32.6	93.0
	Entrance angle less than 30 degrees	38.0	41.1	96.8
	Area of the sidewalk corner with 10% reduction	10.4	41.0	66.8
Number of samples		170	97	260

In what follows, to find out the factors affecting the usage of the bicycle lane, by using data in areas A, B and C, a logical regression model of the bicycle lane usage is bulit, as follows:

$$\log \frac{P}{1-P} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \quad (1)$$

where P is the probability of the bicycle lane usage ($0 \le P \le 1$) and X_i, β_i, $i \in [1,...,n]$ are independent variables and corresponding parameters. And, β_0 is the constant. The estimation results are provided in Table 3. Additionally, the definition of the angle from the sidewalk corner to the entrance of the bicycle lane is illustrated in Figure 2. By Table 3, as expected, reducing the entrance angle and the area of the sidewalk corner can significantly improve the usage of the bicycle lane. And, decreasing the ratio of the number of pedestrians and cyclists near the bicycle lane entrance to the total number of pedestrians and cyclists in the sidewalk corner and the ratio of the number of opposite cyclists to the total number of cyclists in the bicycle lane can also promote the use of the bicycle lane, to some extent. The sensitivity analysis results presented in Table 4 show that to what extent the adjustment of the variables of interest would affect the bicycle lane usage. It is clear that reducing the entrance angle of the bicycle lane to less than 30 degrees can noticeably improve the bicycle lane usage, especially for bicycle lanes in areas A and C.

ANALYSIS ON THE CYCLING SAFETY

We now move to analyzing the cycling safety at the considered intersections. The measure used to estimate the cyclist safety is proposed by Allen et al. (1978). The data used in this section were collected at Mitsukura and Gofuku intersections due to their similar scale and different bicycle lane designs.

As shown in Figure 2, when the cyclist and the left-turn vehicle cross the crosswalk simultaneously, according to the approaching trajectory of the motor vehicle, the conflict point can be identified. When the cyclist (the leading object) passed this conflict point, record this time point as X. The time point when the left-turn vehicle (the following object) passed the conflict point is recorded as Y. The post-encroachment time (PET) index is defined by the time difference between X and Y,

$$\text{PET} = \text{Y} - \text{X} \quad (2)$$

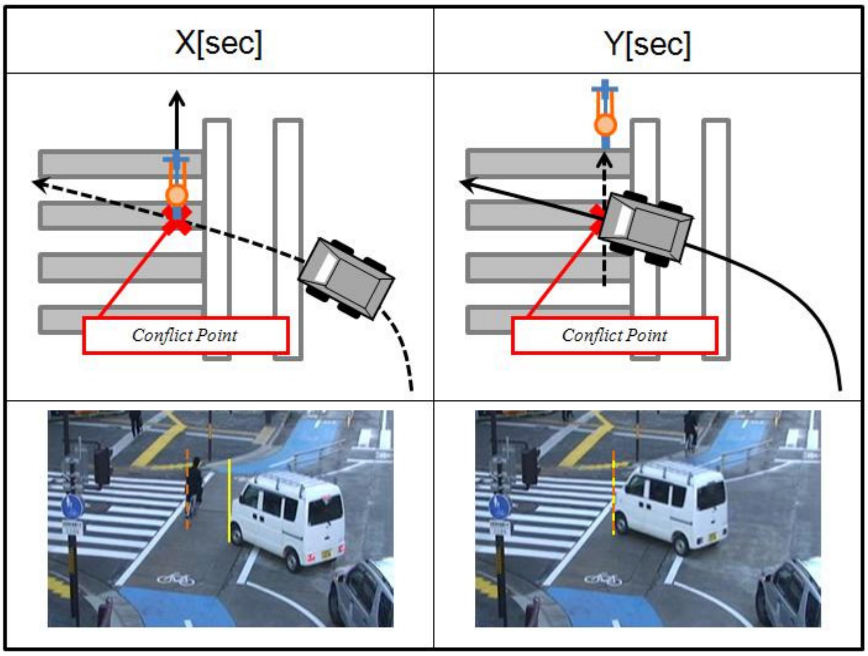

Figure 2 – The illustration of the conflict point

Table 5 – The ratios of normal and dangerous crossing instances at Mitsukura and Gofuku intersections

Intersection	Moving direction	Ratio of normal crossing instances	Ratio of dangerous crossing instances	Number of samples
Mitsukura	Northbound	12%	2.3%	342
	Southbound	9.4%	0.8%	128
Gofuku	Eastbound	14.5%	1.8%	55
	Westbound	16.9%	2.8%	177

Moreover, based on the mean of crossing time for all recorded cyclists -- 3.0 seconds, we distinguish two kinds of instances when cyclists and left-turn vehicles are crossing the crosswalk simultaneously -- the normal crossing instance and the dangerous crossing instance. The normal crossing instance is defined by the PET less than 3.0 seconds and the dangerous crossing instance is defined by the PET less than 1.5 seconds.

The ratios of normal and dangerous crossing instances at Mitsukura and Gofuku intersections are presented in Table 5. We can see that the ratios of normal and dangerous crossing instances at Gofuku intersection are higher than that at Mitsukura intersection, except the ratio of dangerous crossing instances for northbound cyclists at Mitsukura intersection. To some extent, this indicates that riding in the bicycle lane directly connecting the crosswalk is more dangerous than riding in the bicycle lane connecting the sidewalk corner.

ANALYSIS ON THE CYCLISTS' PATH-CHANGING DECISIONS

In this section, we investigate the path-changing decisions for cyclists riding from A to F areas and in the opposite direction, using the data collected by several video cameras working simultaneously.

Figure 3 demonstrates the detailed distribution of path-changing decisions for all cyclists riding from areas A to D. From the figure, we can see four remarkable path-changing locations, riding from D to C and from B to A for northbound cyclists and from E to F and from C to D for southbound cyclists.

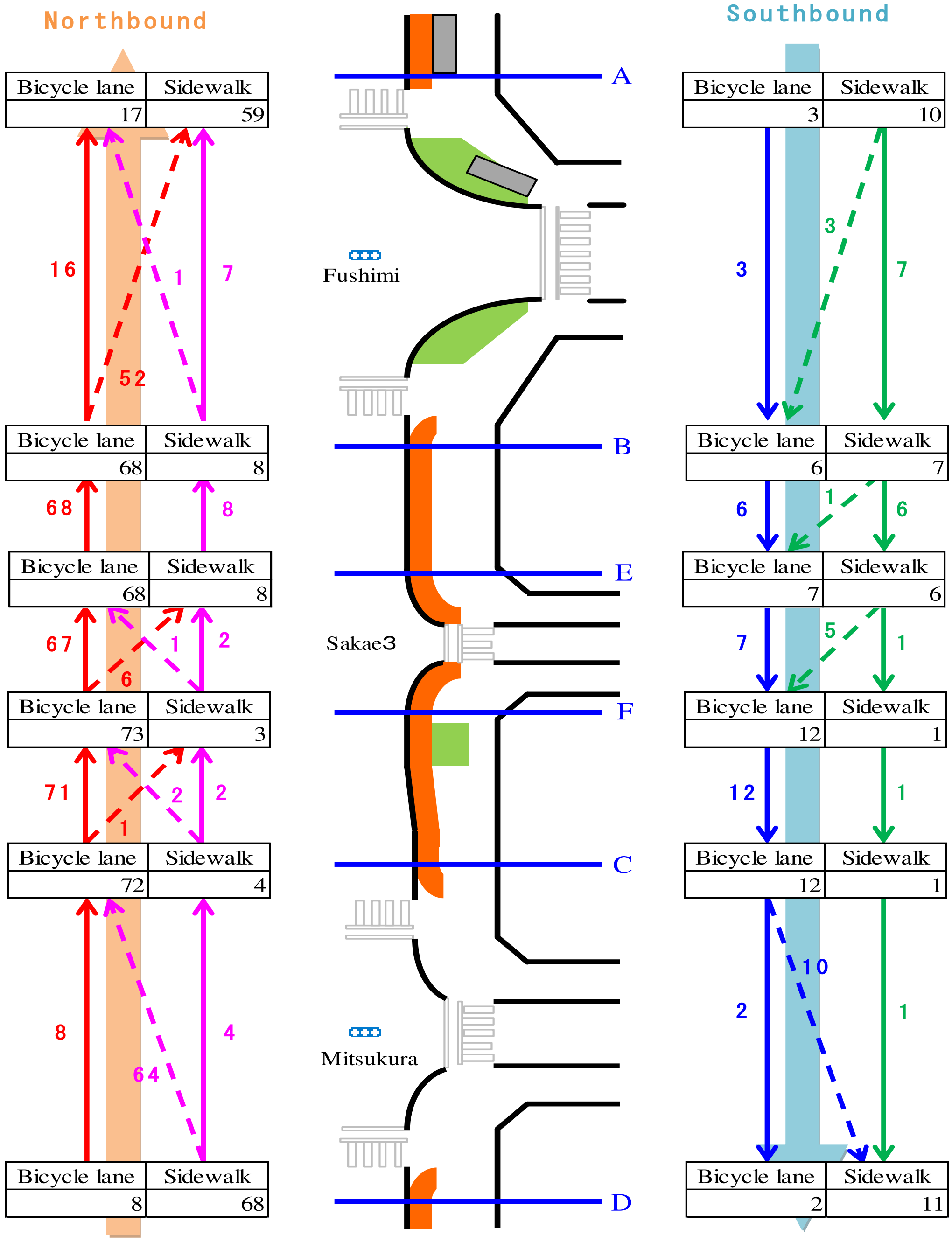

Figure 3 – The illustration of path-changing decisions for all cyclists

Table 6 – The Statistic summary for northbound cyclists

Path-changing	Number	Gender		Bicycle type			Speed[m/s]	Density	
		Male	Female	Utility	Small wheel	Sports		BL	SW
BL→SW	3 (3.9%)	3	0	1	0	2	4.86	0.046	0.057
SW→BL	11 (14.5%)	6	5	8	3	0	4.25	0.071	0.031
SW→BL →SW	55 (72.4%)	31	24	42	11	2	4.15	0.068	0.023
BL→SW →BL→SW	1 (1.3%)	0	1	1	0	0	3.57	0.062	0.000
Total	76	45	31	56	15	5	4.16	0.064	0.032

※BL and SW are short for bicycle lane and sidewalk

Table 7 – Estimation results for the path-changing model

Explanatory variables	Parameters
Mean speed, exclusive of the speed after the signals turn red [m/s]	-1.88***
Mean density in the bicycle lane [person/m^2]	30.18*
Constant	3.63*
Percent correctly predicted [%]	93.26
Nagelkerke R-square	0.254
Number of samples	89

* and *** denote the significance of corresponding parameters at 1% and 10% confidence level.

Two subway entrances near area A and a bus stop near area D is considered as the primary reason for the dramatic path-changing decisions. For subject cyclists, most of whom are local residents, they are familiar with their routes. We can see most cyclists riding in the sidewalk in area D, in order to avoid passengers waiting in the bus stop or getting off a bus. Hence, after crossing the Mitsukura intersection, most northbound cyclists riding in the sidewalk decide to change into the bicycle lane. And, most southbound cyclists in bicycle lane start to use the sidewalk at downstream of section C. Due to the crowd gathering near area A, most of whom are from the subway entrances or pedestrians waiting signals, it is hard for northbound cyclists to enter the bicycle lane entrance near area A. As a result, most northbound cyclists have to ride in the sidewalk.

Table 6 lists the statistic summary for northbound cyclists, where speed is the mean value of all corresponding cyclists' speed before signals turn red. According to (TSUKAGUCHI and MORI 1987), we set the area occupied by a cyclist to be 12.8 m^2 and that occupied by a pedestrian to be 5.0 m^2, and then the density in the bicycle lane or the sidewalk when cyclists are travelling on their paths can be defined. The density value in Table 6 is the mean value for all subject cyclists. From Table 6, around 74% cyclists changed their paths more than twice, which implies that changing path is very common for cyclists due to the easy manoeuvrability of bicycles and is worthy of consideration in discussing cyclist behaviour.

To explore the factors affecting the cyclists' path-changing decisions, a logistical regression model is employed, in which the dependent variable is non path-changing decision. The estimation results are listed in Table 7, where the mean speed and the mean density are the mean values for all subject cyclists.

From Table 7, the mean speed has negative effect on non path-changing decisions, that is, when a cyclist is riding with the relatively high speed he/she tends to change the current path. This implies that for most cyclists with high speed they are reluctant to reduce their current speed and resort to changing paths to maintain the current speed. By the parameter of the mean density, with the increase of the number of bicycles in the bicycle lane, the cyclists tend to stay in the current lane. Namely, cyclists in the sidewalk tend to stay in the sidewalk and cyclists in the bicycle lane tend to maintain current lane.

CONCLUSIONS

In this study, by using the data collected at four intersections with the different design of the bicycle lane in Nagoya, Japan, the analysis on the bicycle lane usage, cycling safety and path-changing decisions is conducted, to comprehensively explore the operation of the bicycle lane at intersections. The interesting findings in this research are as follows:

1. The ratio of the width of the bicycle lane to the width of the sidewalk significantly affects the bicycle lane usage. Besides, the design that the bicycle lane directly connects the crosswalk also plays an important role in the bicycle lane usage. The usage of bicycle lanes directly connecting the crosswalk at Gofuku intersection where the ratio of the width of the bicycle lane to the width of the sidewalk is 3.0 m / 3.5 m is more than 83% during data collection periods.
2. By developing the bicycle lane usage model, we know that the reduction of the entrance angle and the area of the sidewalk corner can significantly improve the usage of the bicycle lane. And, decreasing the ratio of the number of pedestrians and cyclists near the bicycle lane entrance to the total number of pedestrians and cyclists in the sidewalk corner and the ratio of the number of opposite cyclists to the total number of cyclists in the bicycle lane can also promote the use of the bicycle lane. In addition, from the sensitivity analysis of the proposed model, it is also clear that when the entrance angle is set as less than 30 degrees, the bicycle lane usage can be dramatically improved.
3. By defining the PET index that reflects the safety level of cyclists when crossing the crosswalk, we investigate the cycling safety at two intersections with the similar scale but the different bicycle lane designs. We find that cyclists riding in the bicycle lane directly connecting the crosswalk are more likely to incur the conflicts with motor vehicles, compared to those riding in the bicycle lane connecting the sidewalk corner.
4. From the statistic summary for northbound cyclists riding through three successive intersections, changing the path more than 2 times is very common for most cyclists due to the easy manoeuvrability of the bicycle. Two locations where path-changing behaviour often occurs are identified. Two subway entrances and a bus stop situated in the two locations are considered to be the primary reason for path-changing behaviour. A path-changing model reflects that cyclists with the high speed tend to change their paths and the increase of the density in the bicycle lane can limit the path-changing behaviour.

This research provides some important insights into the operation of the bicycle lane at intersections in Japan, which would be useful to researchers or practitioners working on the bicycle lane planning and design. However, analysis on the pedestrian behaviour is not included in this study. As is well known, pedestrian behaviour potentially has some influences on the bicycle lane usage and pedestrian-cyclist conflicts, especially for the mixed cyclists and pedestrian traffic in the sidewalk corner. The works in this regard are ongoing.

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