Subjective Evaluation for the Driving Conditions at Signalized Intersection and Roundabout by Before-After Analysis

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ABSTRACT

This study investigated safety confirmation behaviors such as looking both ways near a crosswalk and the evaluation of driving satisfaction before and after the conversion of a signalized intersection (SI) to a roundabout (RAB) in Iida city, Japan. Drivers' behaviors when entering or exiting the SI and RAB were captured by two in-vehicle video cameras, a drive recorder, and a GPS logger. In addition, after navigating a route, the participants were asked to evaluate driving satisfaction using a 4-point rating scale. The instantaneous speeds and distances of safety confirmation, the necessary deceleration rate for safe stopping, the number of safety confirmation behaviors, and the subjective evaluation of driving satisfaction, were completely analyzed at the SI and RAB. The effectiveness of converting SIs to RABs was quantitatively investigated. Some interesting findings were presented, which can provide some helpful guidance on discussions concerning the feasibility of introducing RAB in Japan.

INTRODUCTION

According to the traffic accident statistics compiled by the National Police Agency in Japan (2013), the total number of traffic accidents has been gradually decreasing year by year, and only 4,411 fatal traffic accidents occurred in 2012. However, it is also noted that among all traffic facilities more than half of the traffic accidents happened at or near intersections. Therefore, it is necessary to take effective measures to improve traffic safety at intersections.

Over the last 20 years, more and more intersections have been converted to roundabouts (RABs) in Europe and USA as an effective control facility for less traffic (Elvik 2003, Flannery and Datta 1996, Robinson et al. 2000, Persaud et al. 2001). The RAB is a roadway intersection designed to facilitate traffic flow and reduce the incidence of serious accidents. RABs have one-way traffic in a circulatory roadway around a central island, together with entries and exits separated by splitter islands. Unlike a traffic signal, wherein the vehicle entrance to a junction is controlled by allocation of green times (Abu-Lebdeh et al. 2007, Heydecker 2004), vehicles entering RABs must give way to vehicles already in it. Compared with unsignalized and signalized intersections, RABs have two advantages: capacity and safety. The RAB has a larger capacity than intersections as left turns are omitted (Sisiopiku and Oh 2001). Moreover, because all traffic flows are required to circulate around the central island in the same direction, conflict points are largely reduced. Hence, the RAB can reduce the number and severity of traffic accidents (Persaud et al. 2001, Stuwe 1991). It is also believed to have an effect on reducing pollutant emissions (Coelho et al. 2006, Höglund 1994).

In recent years, comprehensive research on the feasibility of introducing RABs have also been conducted in Japan (IATSS Report 2011, 2012). In particular, compared with signalized intersections (SIs), the RAB is more effective during a power outage caused by earthquakes or tsunamis, which occur often in Japan (Nakamura et al. 2009, Munehiro et al. 2009, Takigawa et al. 2010). As a result, on February 5th 2013, SIs in Iida city was converted to RABs for the first time in Japan.

Although there were a few studies concerning the effects of RAB conversions in the U.S.A. (Persaud et al. 2001, Gross et al. 2013), a before-after study associated with driving behaviors has not been conducted in Japan, which has left-hand traffic and drivers may not have been accustomed to the new facility. The current study therefore investigated the safety confirmation behaviors and the evaluation of driving satisfaction before and after the conversion of SIs to RABs in Iida city using driving experiments.

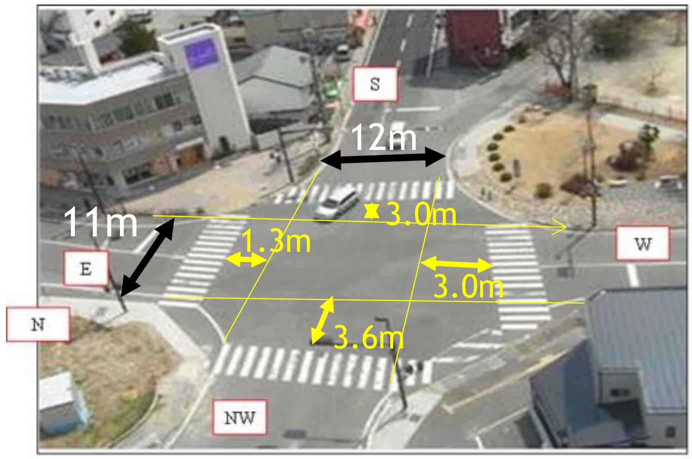
STUDY SITES AND DRIVING EXPERIMENTS

On February 5, 2013, the Towa-cho SI was converted to a RAB for the first time in Japan. FIGURE 1 displays the geometries of the SI and RAB. The setback distance of crosswalk from the circulatory road for all legs are set 5.5 m for the RAB, which is longer than that for the SI. All the entries of the RAB is controlled with a stop sign because yield traffic control is not permitted in Japan. In addition, the roads follow the left-hand traffic convention. Driving experiments were conducted:

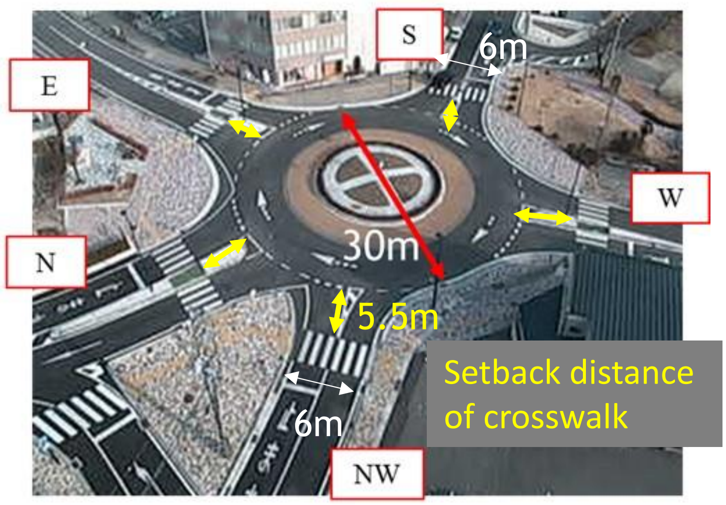
･before the conversion on May 8th and 9th, 2012, with four participants,

･immediately after the conversion on February 5th and 6th, 2013, with two participants, and

･after the conversion on May 8th and 9th 2013 with four participants.



a. Towa-cho SI (before conversion)



b. Towa-cho RAB (after conversion)

FIGURE 1 Geometries of the SI and RAB

The experimental vehicle was equipped with two in-vehicle video cameras, a drive recorder with GPS locator-equipped, and a stand-alone GPS logger. The equipment specifications are summarized in TABLE 1. Data on vehicle movements and surrounding traffic conditions were obtained, along with data on the in-vehicle driving behaviors of participants every 0.1 s. The equipped experimental vehicle and the setting of in-vehicle video cameras are shown in FIGURE 2.

Considering driving fatigue, we divided all the driving routes into two types. The participants were required to run 10 routes of only one type at a time. The routes in each type are identified in FIGURE 3. After navigating a route, the participants were asked to evaluate driving satisfaction about the route using a 4-point rating scale: 1 - very easy, 2 - easy, 3 - slightly difficult, and 4 - difficult. In addition, when the participant confirms the existence of pedestrians at the entrances or exits of intersections as shown in FIGURE 4, they notify the surveyor sitting in the passenger seat of their confirmation behavior by speaking out 'I confirmed it'. The surveyor then recorded the time into the drive recorder manually. Therefore, we obtained information about participants' safety confirmation behaviors and the vehicle movements such as the vehicle speed, and the location at that time. The required time for each test type was approximately 40 minutes.

TABLE1 Equipment specifications

Equipment	Video-camera Recorder	Drive Recorder	GPS Logger
Product name (Maker)	HDR-CX590V (SONY)	SRcomm (Data-tech)	G-Rays2 (Wintec)
Size: W*H*D [mm]	54*64*116	178*140*55	64*40*17
Weight[g]	320	800	55
Sampling frequency	5Mbps	10Hz	1Hz

FIGURE 2 The equipped experimental vehicle and the setting of in-vehicle video cameras

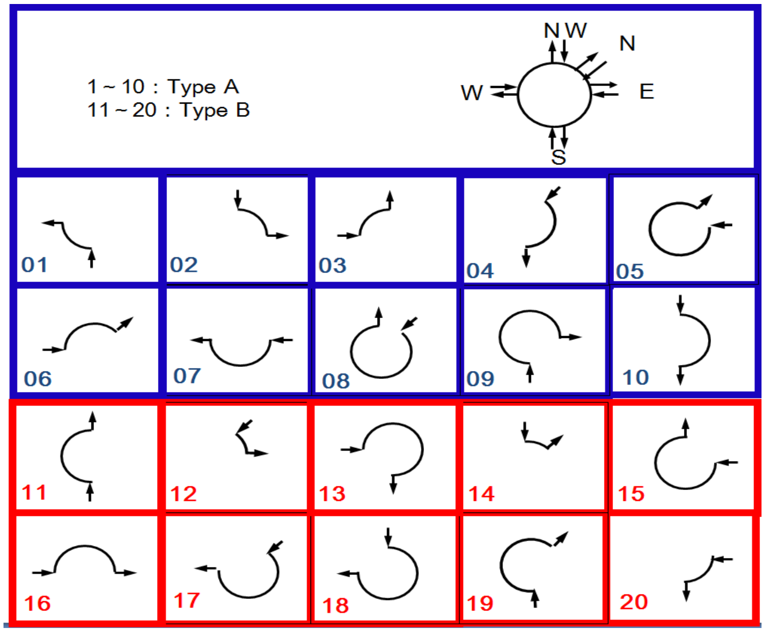


FIGURE 3 Driving routes into types A and B

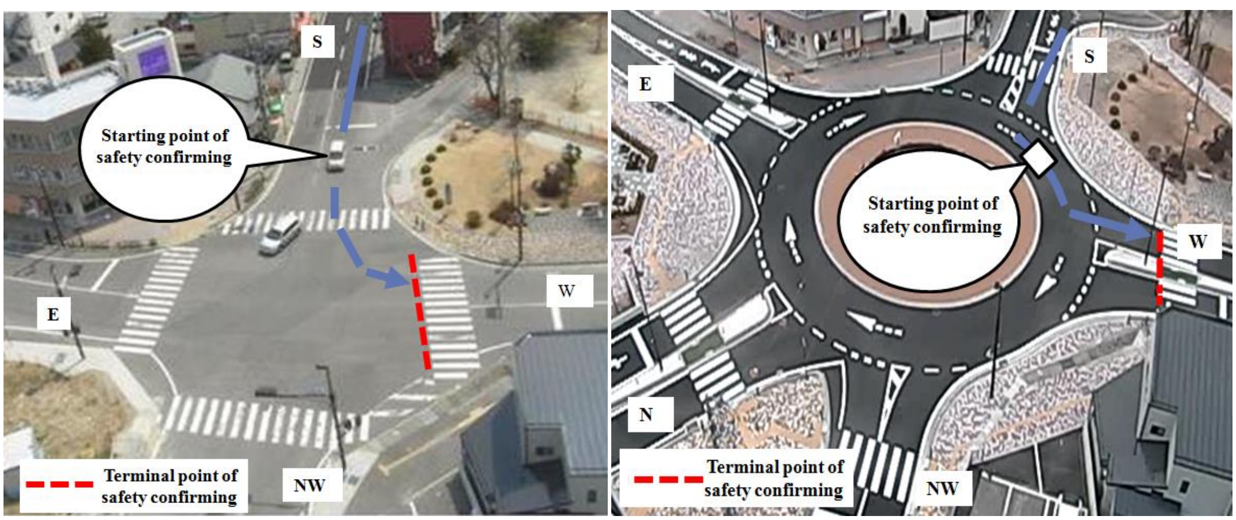


FIGURE 4 Definition of starting and terminal points for safety confirmation

DRIVING BEHAVIORS AT THE EXITS OF SI AND RAB

In this section, both the driving behaviors and vehicle movements at the exits of the SI and RAB were investigated. The T-test is used to explain the difference between the two groups. In this study,*, **, and *** denote that the differences are statistically significant at the 1%, 5%, and 10%

level, respectively. In addition, based on left turns and right turns, driving behaviors are divided in two groups.

Analysis of instantaneous speeds of safety confirmation at the exits of the intersection

The instantaneous speeds when the participants start confirming traffic conditions at the crosswalks or on the opposite sides of roads can be obtained by the driving recorder. The statistical summary of the instantaneous speeds collected before the conversion (SI), immediately after the conversion (RAB 1) and after the conversion (RAB 2) are presented in FIGURE 5.

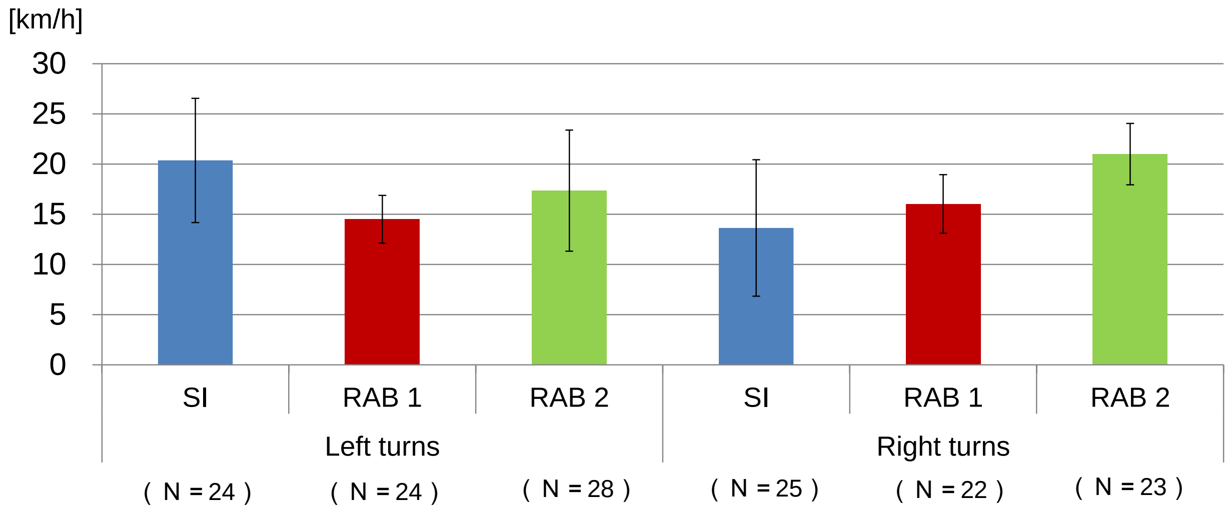


FIGURE 5 The statistical summary of instantaneous speeds when confirming safety at the exits of SI and RAB

It is noted that for left turns, the mean speed when confirming safety at RAB 1 are clearly lower than the mean speed at the SI. The T-test (T-value = 5.10*) also reflects this difference. Due to fact that the vehicle is required to stop in front of crosswalks, before entering the RAB in accordance with the stop sign, and has to give way to vehicles already in the RAB, it is very hard for the vehicle to accelerate to a high speed over the short driving distance. Owing to this configuration of RAB, the vehicle speeds are constrained. On the contrary, for right turns, the mean speeds at RAB 1 and RAB 2 are greater than that at the SI. From the T-test, the differences are also statistically significant (T-value = -1.71***, 4.90*, respectively). When turning right, drivers have to stop temporarily within the SI and check traffic conditions at crosswalks or on opposite sides of the roads. Such driving behaviors limit vehicle speeds at SIs. It is also found that the standard deviation of speeds at RAB 1 and RAB 2 is less than that at the SI. Hence, the driving behavior of right-turning traffic at RAB is more stable and smooth than traffic at the SI.

Analysis of distances of safety confirmation at the exits of the intersection

The starting and terminal points of safety confirmation are defined in FIGURE 4. In driving experiments, participants were asked to notify the surveyor sitting in the passenger seat of their confirmation behaviors by speaking out ‘I confirmed it’. The surveyor recorded the time by using the drive recorder. Therefore, the starting points of safety confirmation can be obtained. The terminal points of safety confirmation are represented by the red lines in FIGURE 4. The statistical summary of the distances between starting and terminal points at the exits of intersection is displayed in FIGURE 6.

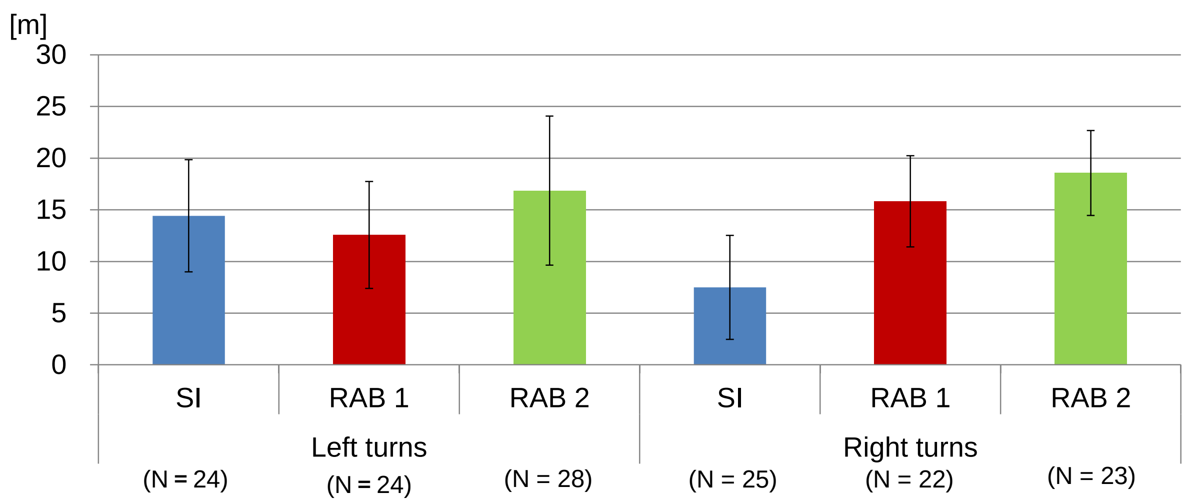


FIGURE 6 The statistical summary of distances between starting and terminal points at the exits of SI and RAB

From FIGURE 6, for left turns, the differences between the SI and RAB in distances are not significant (T-value = 1.38, -1.35, respectively). However, for right turns, the distances between starting and terminal points are significantly different based on the T-test (T-value = -5.58*, -8.30*, respectively) at the SI and RAB. The mean distances at RAB 1 and RAB 2 are greater than 15 m, but at the SI, the value is less than 8 m. This indicates that when turning right at the RAB, the driver can confirm safety earlier than when turning right at the SI.

Necessary deceleration rate for safe stopping at the exits of intersection

In this research, in order to evaluate potential traffic risks for pedestrians when turning left or right at the exits of the SI and RAB, we define the necessary deceleration rate for safe stopping before the crosswalk by using the instantaneous speeds and distances of safety confirmation.

The necessary deceleration rate for safe stopping is represented by the following equation

$$NDR = \frac{{v_t}^2}{2x_t} \qquad (1)$$

where vt is the instantaneous speed when the driver is checking traffic conditions and xt is the distance between the starting point and internal point of safety confirmation. In addition, we assume that the deceleration is linear.

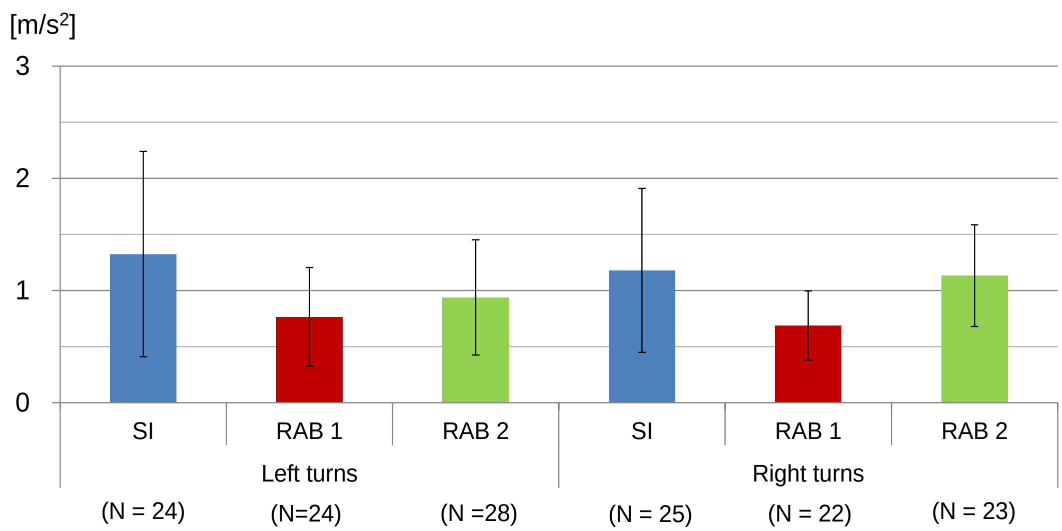


FIGURE 7 The statistical summary of the necessary deceleration rate before the crosswalk at the exit of intersection

FIGURE 7 displays the statistical summary of NDR. It is noted that for both left and right turns, the mean NDR at the RAB is obviously less than the mean NDR at the SI. With the T values = 3.30*, 1.84*** respectively, such differences are also statistically significant. For left turns, there is a small difference in distances between starting and terminal points of safety confirmation at the SI and RAB. However, the instantaneous speeds of safety confirmation at the RAB are clearly lower than those at the SI. On the another hand, for right turns, although vehicles are faster at the RAB than vehicles at the SI when checking traffic conditions, the starting time of safety confirmation at the RAB is earlier than that at the SI. The NDR analysis indicates that the RAB can constrain severe deceleration and has an effect on comfortable driving compared with the SI.

Number of safety confirmation behaviors

Subsequently, we investigated the frequency of drivers' safety confirmation behaviors through the video cameras. In this research, safety confirmation behaviors characterized as ‘with rotating his/her head’, ‘with eye movement’ and ‘with both rotating his/her head and eye movement’ are focused on and treated as the same. For each participant, the number of safety confirmation behaviors between the starting and terminal points are counted using image analysis. The frequency of the safety confirmation behaviors at the SI and RAB is statistically analyzed, as shown in FIGURE 7.

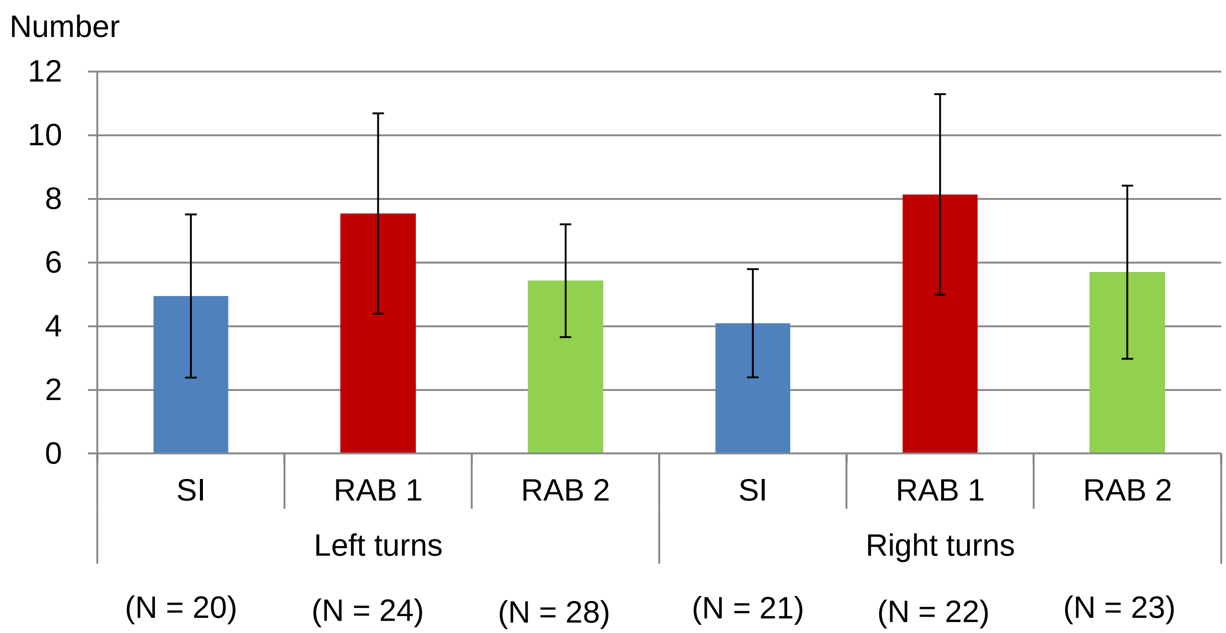


FIGURE 8 Number of safety confirmation behaviors at the SI and RAB

From FIGURE 8, for both left and right turns, the mean number of safety confirmation behaviors at RAB 1 is higher than the mean number at the SI. The difference in the mean number is also statistically significant, with a T-value of -2.66* and -5.51* for left and right turns, respectively. However, the differences between the SI and RAB 2 for left turns are not statistically significant, though the differences at right turns are still statistically significant. It can be considered that the test drivers at RAB 2 became familiar with the left turning drive at the roundabout. This suggests that drivers are more cautious when going through the RAB than when driving at the SI.

SUBJECTIVE EVALUATION FOR DRIVING SATISFACTION

In Persaud et al. (2001) and Gross et al. (2013), the observed crash data were used to check the safety effectiveness of converting SIs to RABs. The subjective evaluation was seldom carried out in previous studies.

Numerical scores of driving satisfaction

In this study, after running through a route, the participant was asked to evaluate driving satisfaction about the route, by using a 4-point rating scale: 1 - very easy, 2 - easy, 3 - slightly difficult, and 4 - difficult. To facilitate statistical analysis, the Likert Scale (Allen et al. 2007) is applied to convert the qualitative responses to the quantitative scores. The Likert Scale equation is shown below and the numerical values based on driving survey data are listed in TABLE 2.

$$\sigma = \frac{y_{i-1} - y_i}{R_i} \qquad (2)$$

Here, σ is the sigma value, y_i is the y-value of normal distribution and R_i is the relative frequency of each item i

TABLE 2 The converted numerical scores using the Likert Scale

Study sites	SI, RAB 1, and RAB 2			
Variables	y_i	R_i	σ	Score
1: Very easy	0.22	0.14	-1.59	100
2: Easy	0.33	0.60	-0.17	49.36
3: Slightly difficult	0.04	0.24	1.15	16.40
4: Difficult	0.00	0.02	2.47	0

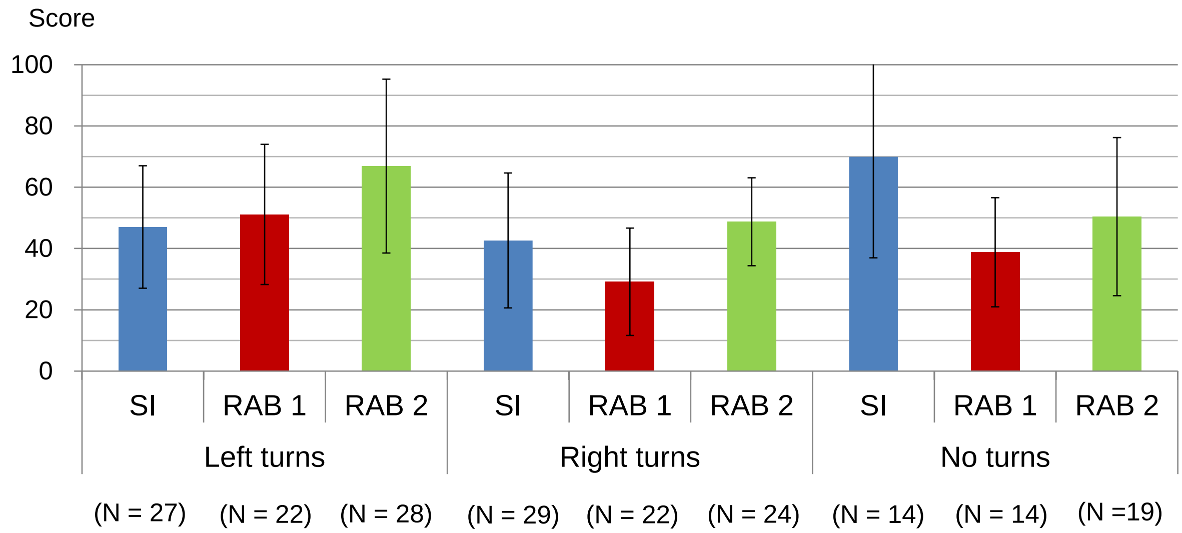


FIGURE 9 Evaluation scores of driving satisfaction at the SI and RAB

The evaluation scores of driving satisfaction at the SI and RAB are illustrated in FIGURE 9. For left turns, there is no significant difference in evaluation scores at the SI and RAB 1; however, the differences between SI and RAB 2 are statistically significant (T-value = -2.99*). Therefore, when turning left, drivers feel at ease driving in RAB 2 in accordance with habituation. On the other hand, for right turns and no turns at the SI and RAB 1, apparent differences in driving satisfaction are observed. The T-values for right turns and no turns are 3.58* and 3.11*, respectively. The mean score at the SI is clearly higher than the mean score at RAB 1. It means that drivers felt less satisfied when running immediately after introducing the RAB. This may be due to the fact that most drivers have not become accustomed to the RAB. In addition, the roads near the intersection were under construction and traffic was locally constrained when conducting driving experiments at RAB 1. To some extent, such factors may impact driving satisfaction at RABs. Though there are no differences between the SI and RAB 2, it is also found that the drivers' evaluation is improved from this same figure.

Discriminant analysis of driving satisfaction

To find out the factors that influence driving satisfaction, discriminant analysis was conducted at the RAB. The analysis results are listed in TABLE 3. Here, if the sign of unstandardized or standardized parameter of a variable is negative/positive, the value of the corresponding variable driving satisfaction will also be increased/decreased.

From TABLE 3, if there is a leading vehicle within the RAB, driving satisfaction will be decreased. If the instantaneous speed when confirming safety is less than 15 km/h, drivers will evaluate the driving at a low level. When the instantaneous speed of safety confirmation is greater than 15 km/h, drivers will be satisfied with traffic conditions. When the gradient of the RAB is less than 180º, drivers can achieve high satisfaction.

TABLE 3 Discriminant analysis for evaluation of traffic conditions at the RAB

Variable	Unstandardized parameter	Standardized parameter	f-value	Significance
Constant	-0.33			
Dummy of existence of leading vehicle within RAB	2.25	0.81	16.93	0.00
Dummy of gradient of RAB less than 180º	-0.53	-0.20	3.37	0.07
Dummy of instantaneous speed of safety confirming between 10 km/h and 15 km/h	5.14	0.56	5.94	0.01
Dummy of instantaneous speed of safety confirming between 15 km/h and 20 km/h	-0.75	-0.28	2.82	0.09
Dummy of instantaneous speed of safety confirming between 0 km/h and 5 km/h	5.14	0.56	5.94	0.01
Canonical correlation	0.62			
Wilks Lambda	0.62			
Significance	0.00			
Percentage of correct predictions	87.30%			

CONCLUSIONS

As an effective control facility for lower traffic, RABs have become popular in Europe and the U.S.A. In recent years, the feasibility of installing RABs in Japan has also been comprehensively discussed. On February 5th, 2013, a SI in Iida city was converted to a RAB for the first time in Japan. In this research, driving experiments were conducted at the SI before the conversion and the RAB immediately after and a longer time after the conversion). A before-after study associated with driving behaviors was conducted. The instantaneous speeds and distances of safety confirmation, the necessary deceleration rate for safe stopping, the number of safety confirmation behaviors, and subjective evaluations for driving satisfaction, were completely analyzed for left and right turns at the SI and RAB. The study's findings are as follows:

1. For left turns, the mean speed when confirming safety at the RAB are clearly lower than the mean speed at the SI. Owing to the configuration of the RAB, the speed is constrained. For right turns the mean speeds at RAB 1 and RAB 2 are greater than that at the SI. The standard deviation of the instantaneous speeds at the RAB is less than that at the SI. Hence, traffic at the RAB is more stable and smooth than traffic at the SI.
2. From the analysis of distances of safety confirmation, for right turns, the distances between starting and terminal points are significantly different at the SI and RAB. It indicates that when turning right at the RAB, the driver can confirm safety earlier than when turning right at the SI.
3. For both left and right turns, the mean necessary deceleration rate at the RAB is less than that at the SI. This means that the RAB can constrain severe deceleration and has an effect on comfortable driving compared with the SI.
4. The mean number of safety confirmation behaviors at the RAB is more than the mean number at the SI for both left and right turns. This indicates that drivers are more cautious when going through the RAB than the SI.
5. It is also noted that for left turns, there are no significant differences in evaluation scores of driving satisfaction at the SI and RAB. For right turns and no turns immediately after introducing the RAB, although the mean score at the SI is higher than the mean score at the RAB, the evaluation for traffic at the RAB were improved with time. This indicates that unaccustomed drivers do not feel burdened by going through the RAB.
6. Discriminant analysis shows that the existence of a leading vehicle within the RAB, the instantaneous speed of safety confirmation, and the gradient of the RAB can significantly influence driving satisfaction.

Although careful consideration was given to the study, there remain some issues needing further discussion. Owing to the small number of participants, limited survey site, the drivers' characteristics such as age, gender, and driving experience, were not thoroughly reflected in the study and the findings are not widely representative. Crash data that can directly show safety benefits of the SI and RAB were not included in the study. These factors will be considered in our future work.

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