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Driving Behavior Analysis at Roundabouts under Snowy and Dry Road Conditions

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ABSTRACT

The number of traffic fatalities has been decreasing in Japan since 2001. However, the life of 4,411 people is still lost in traffic accidents in 2012. Because since 54 percent of traffic accidents are attributed to intersections, safety countermeasures at intersections are indispensable to enhance traffic safety and traffic signals have played an important role in improving safety at intersections. However, since recent disasters such as the Great East Japan Earthquake in March 2011 caused traffic chaos due to major blackouts, roundabouts have been attracting rising attention.

Although the literature review shows that a considerable amount of published reports and studies related to roundabouts, few studies has been conducted under snowy road conditions. Since snow and ice are common meteorological occurrences in many parts of Japan during the winter season, verification of the safety of the roundabouts under snowy conditions are required in order to consider installing roundabouts in these regions.

In this study, aimed at verifying the safety of roundabouts in snowy regions, driving experiments were conducted under snowy and dry road conditions at a single-lane roundabout which is installed on a test track and actual comparable at-grade intersections. In addition to the speed and the acceleration of the test vehicles, driver behavior such as head movement, steering and pedal operations are observed in the experiments. Besides, the tests subjects were asked to indicate easiness to take confirming safety using a 1-to-7 rating scale immediately after the each test. The study results showed that roundabouts are safer than conventional intersections from the aspect of subjective evaluation and driving behavior even under snowy conditions.

Keywords: roundabout, at-grade intersection, safety check, driving behavior, snowy cold region

1. INTRODUCTION

Traffic fatalities in Japan totaled 4,411 in 2012, the twelfth consecutive year of decrease; even so, the number remains high (*1*). Broken down by road type, 54% of traffic accidents occurred at intersections (including 13% near intersections), 41% occurred on road sections with uninterrupted traffic flow and 5% occurred on other types of road. Safety improvements at intersections are strongly desired.

In suburbs, there are signalized intersections where the traffic volume is low and cars often have to wait at red lights even when there is no traffic on the crossing road. At the time of large-scale disasters such as the Great East Japan Earthquake of March 11, 2011, and the large-scale blackout in the Iburi area of November 27, 2011, the traffic signals at intersections did not work and police had to direct traffic manually to secure safety at those intersections for a long time (Photo 1). To solve problems similar to those described above, signalized intersections have been actively under improvement to roundabouts in Western countries since 1980s. A roundabout at an at-grade intersection with a relatively low traffic volume has the benefits of mitigating major accidents, reducing delays caused by waiting for the signal and maintaining functionality at the time of disasters. An example of the benefits of roundabouts improved from conventional signalized intersections is found in a report from the United States, in which such improvement halved the rate of injurious accidents (*2*).

Photo 1. A policeman directs traffic at an intersection where the signals are not working.

In Japan, there are few examples of the introduction of roundabouts. Simulation studies (*3*), test road experiments (*4*), (*5*) and social experiments on roads (*6*), (*7*) have started in recent years; however, roundabouts are not very widely known on a nationwide scale, and they are far from being widely and practically used. In addition, previous studies on roundabouts have tended to address geometric configuration with good visibility under dry road conditions; hence, evaluations of roundabout use under adverse conditions have not been sufficiently accumulated. There is also a lack of knowledge based on driving behavior, of driver education and of dissemination of that knowledge. For example, in the case of introducing roundabouts in snowy cold regions, it is necessary to design geometric configuration and to formulate related measures based on a knowledge of driving behavior on winter roads under poor visibility, such as during snowfall.

This study examines the safety of roundabouts in winter in snowy cold regions by clarifying the influence of the road conditions and intersection structures on driving behavior. To realize this purpose, data on driving behavior at a roundabout and at at-grade intersections in summer (the dry road condition) and winter (the snowy road condition) were collected and analyzed.

2. EXPERIMENT METHOD

2.1. Outline of the Experiment

The subject intersections in this study include five intersections on actual roads in Hokkaido and one test roundabout installed at the Tomakomai Test Track (Figure 1). The experiments were done in winter (January to February 2012) and summer (August 2012). Driving tests were done with test drivers in vehicles equipped with measuring instruments. The winter experiments were done under the condition of snow cover and maximum daily temperature below zero. The summer experiments were done under the condition of dry road. Ten subject drivers (males in their 20s to 50s) were used for each season and type of intersection (Table 1).

Figure 1. Locations of the driving experiments

Table 1. Experimental Condition

	Field	Intersection Type	Date	Number of Subjects	Time	Air Temperature	View	Road Surface Condition
Summer	Tomakomai Test Track	Roundabout	6th. Aug. 2012 7th. Aug.	【10 men】 20's 4men 30's 1man 40's 2men 50's 3men	Daytime	24℃～27℃	Good	Dry
	Atsuma	Signalized Non-signalized	6th. Aug. 2012 7th. Aug.					
	Otaru	Rotary Signalized Non-signalized	9th. Aug. 2012 11th. Aug.			25℃～27℃		
Winter	Tomakomai Test Track	Roundabout	30th. Jan. 2012 31th. Jan.	【10 men】 20's 4men 30's 1man 40's 2men 50's 3men	Daytime	-8℃～-6℃	Good	Compacted Snow & Ice
	Atsuma	Signalized Non-signalized	30th. Jan. 2012 31th. Jan. 3th. Feb.			-6℃～-4℃		
	Otaru	Rotary Signalized Non-signalized	8th. Feb. 2012 9th. Feb.			-6℃		

2.2. Experimental Roundabout

The roundabout for the experiment was designed under the assumption of the intersection of two-way, two-lane roads in a suburban area in Hokkaido, based on the German design guideline for a small, one-lane roundabout (design traffic volume of up to about 10,000 to 25,000 vehicles/day) (*8*). The road width of the circulatory roadway was 5m, the diameter of the central island was 8m, the width of the apron was 4m and the outer diameter of the roundabout was 26m (Photo 2). This experimental roundabout was installed on a flat asphalt intersection at the Tomakomai Test Track of our institute in Tomakomai City, Hokkaido. The roundabout was made by installing marker lines and temporary structures of concrete blocks.

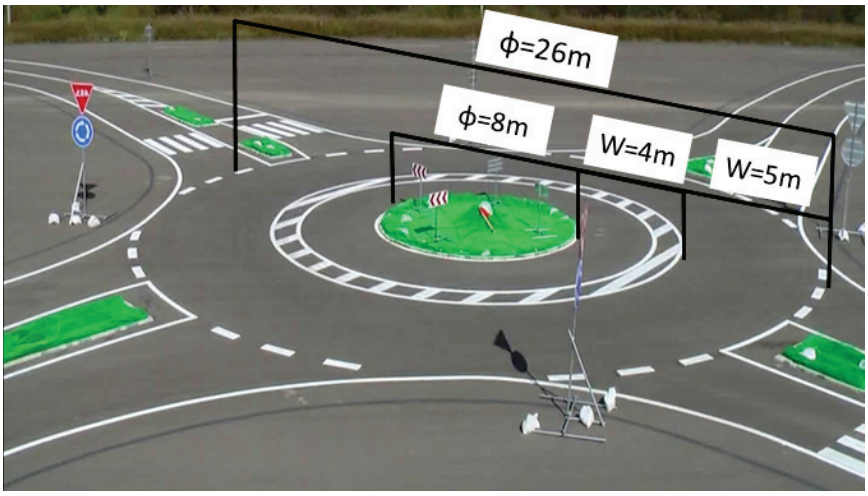

Photo 2. The experimental roundabout

2.3. Intersections on Roads in Service

The subject intersections on roads in service were at five locations: one signalized and one non-signalized four-leg, right-angle intersection in Atsuma Town, Yufutsu Subprefecture, which is near the Tomakomai Test Truck; a rotary with a circulatory roadway of 57m in outer diameter in Sakura District, Otaru City; and one signalized and one non-signalized four-leg, right-angle intersection in Sakura District, Otaru City (Figure 2). The intersections in Atsuma Town are in a suburban area, and those in Otaru are in an urban area. The hourly traffic volume at each location in summer and winter is shown in Table 2.

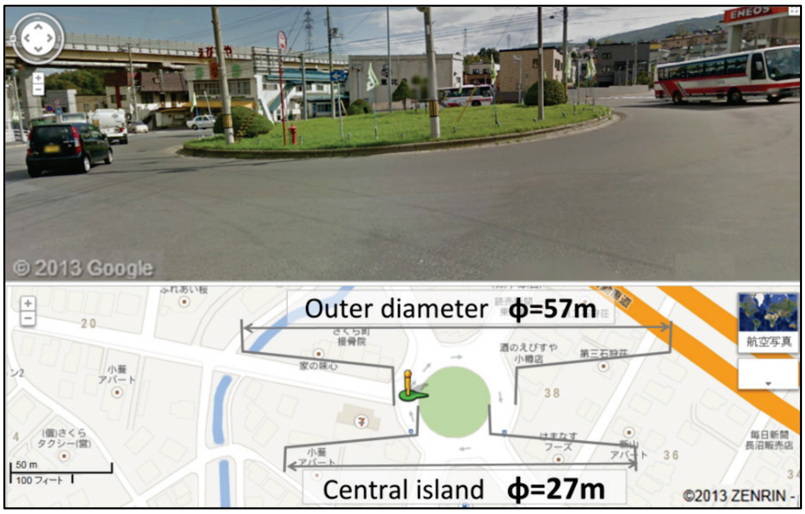

Figure 2. The rotary in Sakura District, Otaru City

Table 2. Hourly traffic volume (total for all approaches):
Measured for one hour immediately before the start of the experiment (between 13:00 and 16:00)

Intersection type	Atsuma Town		Otaru City		
	Signalized	Non-signalized	Signalized	Non-signalized	Rotary
Summer	333	302	417	495	788
Winter	311	236	412	489	662

2.4. Driving Conditions

At the experimental roundabout on the Tomakomai Test Truck, experiments were done by using two driving patterns, both of which used a car with an ordinary driver (the test vehicle) and two cars with support drivers (the support vehicles). In one pattern, one support vehicle came from the right and the test vehicle followed the other support vehicle to the roundabout and entered behind the second support vehicle. This pattern was called the "following pattern". In the other pattern, the test vehicle entered the circulatory roadway while two support vehicles were driving on that roadway. This pattern is called the "single entry pattern".

For the test done on the actual signalized at-grade intersections in Atsuma and Otaru, two patterns were used. In one, the test vehicle stopped at the red light and entered the intersection when the light turned green. In the other pattern, the test vehicle encountered a green light and drove into the intersection without stopping. For the non-signalized intersections, two patterns were used. In one, the subject car driving on the preference (major) road entered the intersection, which was called the "major pattern" , and in the other, the subject car driving on the minor road entered the intersection, which was called the "minor pattern". For the test in Atsuma Town, which is in a suburban area with very little traffic, to avoid the situation in which the test vehicle enters the intersection without any cars around, one support vehicle drove along the major road and entered the intersection at the same time as the test vehicle (Figure 3). At the three intersections in Otaru City, which is an urban area whose traffic volumes at the intersections are greater than those in Atsuma Town, the tests were conducted under ordinary traffic conditions. It was feared that the use of the support vehicles might cause accidents. In addition, each the subjects drove through the intersections one time respectively.

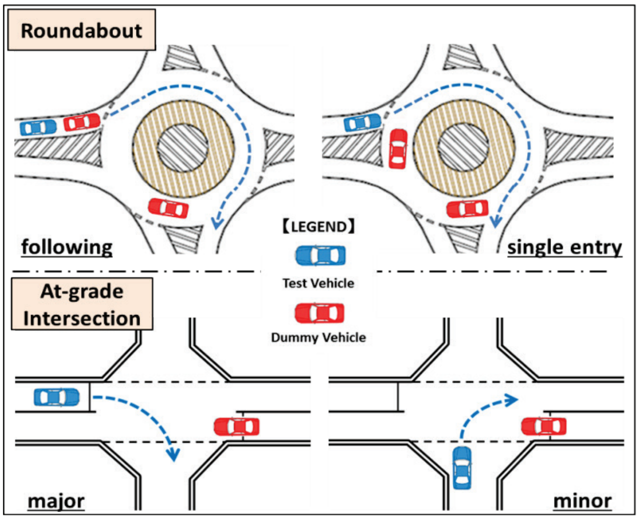

Figure 3. Example of test driving patterns

2. 5. Data Collection and Analysis

In the tests, a conventional passenger car equipped with an accelerometer (DL1, Race Technology Ltd.) and video cameras was used as the test vehicle (Photo 3). The accelerometer was used to gather data on vehicle behavior, such as velocity and lateral acceleration, for analysis. The four video cameras set in the test vehicle took movies of four points: the front view, the interior view that captures the general movements of the driver, the view of steering wheel operation and the view of pedal operation. The four movies were combined into one frame and recorded (Photo 4). Using the images from the four cameras, steering wheel and pedal operations at the time of entering and driving in the intersection were analyzed. To analyze steering wheel operation, a strip of tape affixed to the steering wheel was used as a marker to determine steering angles. The number of pedal applications was determined by counting the number of foot movements between the accelerator pedal position the brake pedal position.

To detect the driver's safety-checking behavior during driving, a gyro sensor (Objet: ATR-sensetech) was mounted on the driver's cap. Movements of the driver's head were analyzed using 3-dimensional acceleration data obtained by a gyro sensor that detected the speed and distance of the head movement. A subjective evaluation of intersection driving safety was done by the driver according to a questionnaire with a 7-point scale after the driver passed through the intersection.

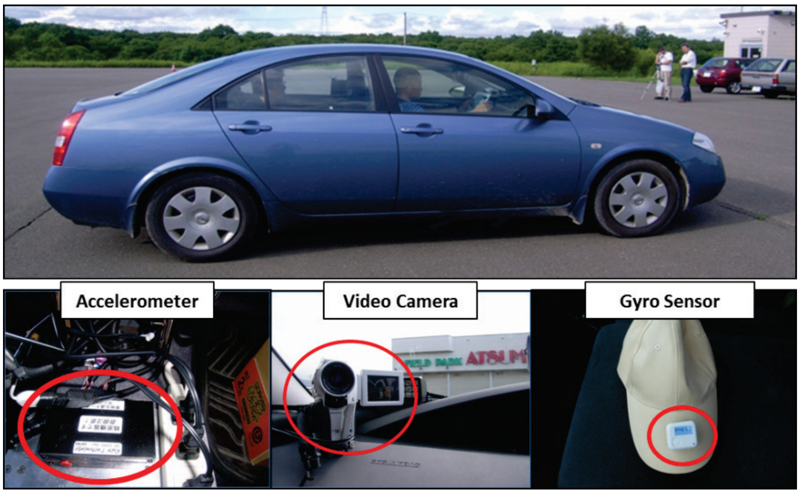

Photo 3. The test vehicle, and the measurement and recording devices

Photo 4. The split screen with four screenshots

3. RESULTS OF EXPERIMENT

3.1. Safety Confirmation Behavior

To determine how the driver's safety confirmation behavior differed according to the intersection type, the speed and distance of head movements detected by the gyro sensor on the cap of the test subject were analyzed. The data show how fast and far the driver moved his head between the time of entering and exiting the intersection.

The head movements at the time of a right turn in the intersection are shown as the speed and distance of the head movements, and the analysis results are shown in Figures 4 and 5. It was found that the values at the 85th percentile of the speed of head movement at the time of driving through the roundabout were lower than those at the at-grade four-leg intersections in summer and winter and that the variance in the results by subject was small. The values for the distance of head movement at the non-signalized intersection (on the minor road) were significantly greater than those at the other at-grade intersections. The values for the distance of head movement for the roundabout were roughly the same as those at other intersections, except for the non-signalized intersection (minor), although the 85 percentile values at the roundabout were slightly greater than those of the other at-grade intersections.

T-tests were done for the speed and distance of head movements at the intersections in summer and winter (Tables 3 and 4). The test results for speed show that the values for the roundabout differ from those for the other intersections. It was found that the distance of head movement tended to be greater at the roundabout than at the other at-grade intersections, because the values for distance of head movement for the roundabout (single entry) are close to 0.05, which is the threshold for determining significance.

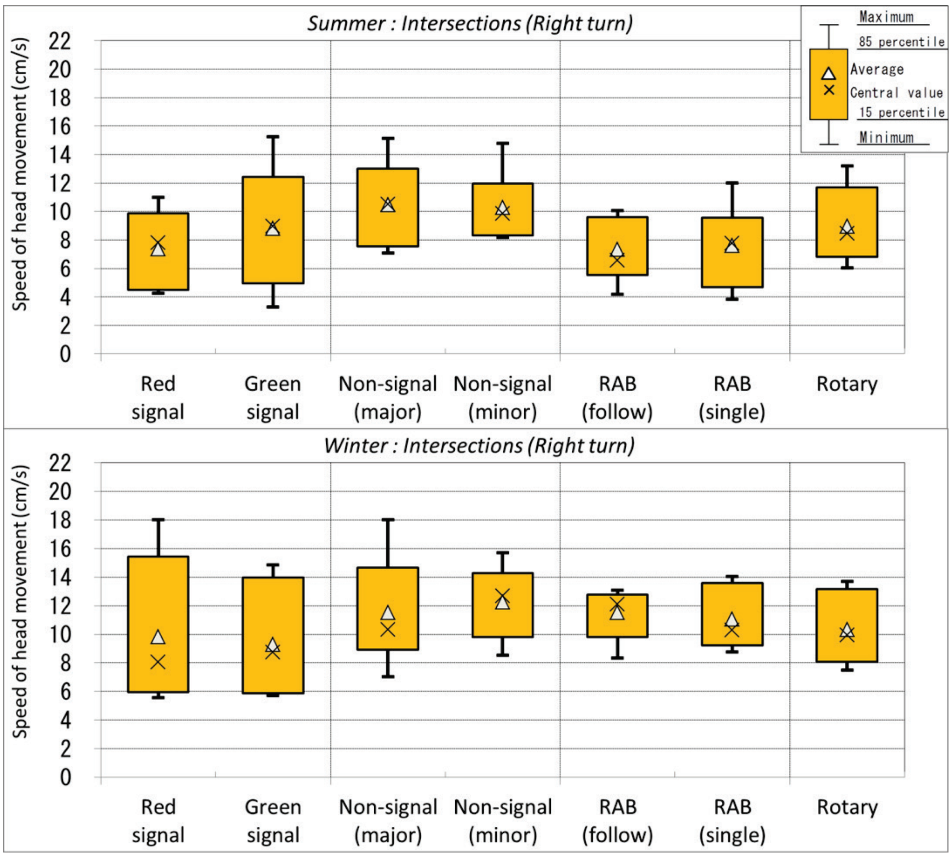

Figure 4. Speed of head movement (right turn)

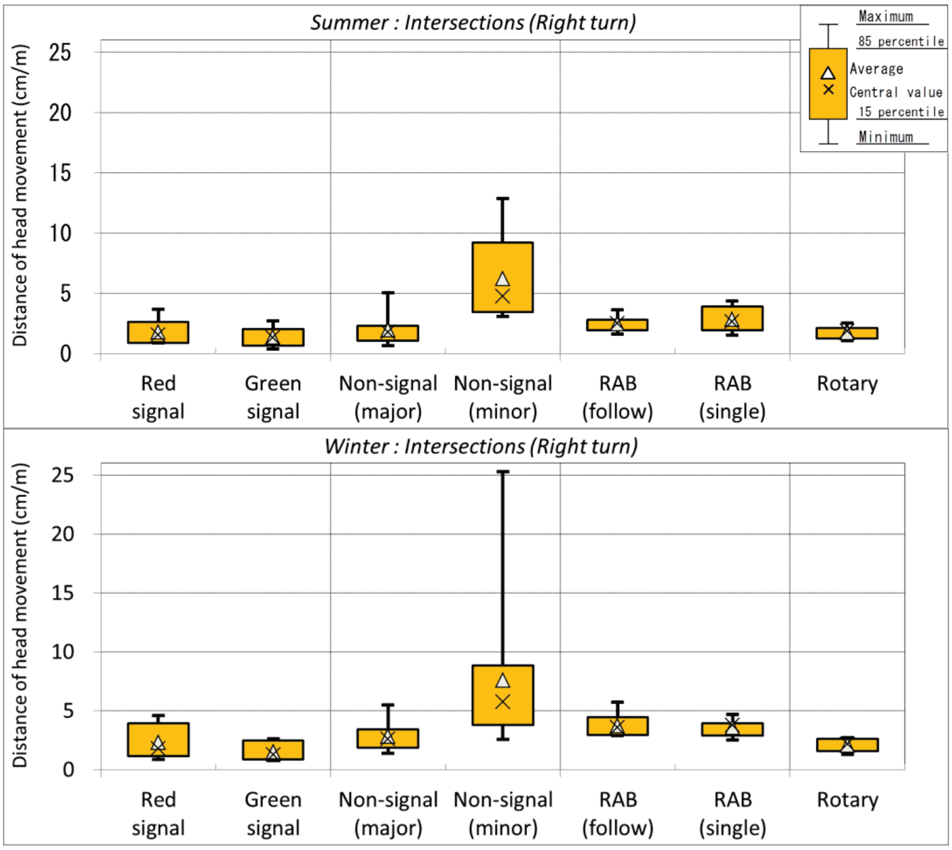

Figure 5. Distance of head movement per 1m traveled (right turn)

Table 3. Comparison between summer and winter:
Speed of head movement (right turn)

Intersection type	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
t-value	1.170	0.322	0.768	2.048	4.768	3.287	1.302
p-value	0.260	0.751	0.452	0.055	0.000 **	0.004 **	0.209

Table 4. Comparison between summer and winter:
Distance of head movement per 1m traveled (right turn)

Intersection type	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
t-value	0.748	0.354	1.637	0.586	3.709	1.979	1.456
p-value	0.466	0.727	0.119	0.565	0.002 **	0.064	0.163

3.2. Steering Wheel and Pedal Operation

Table 5 shows the wheel steering angle per 1m of travel distance at the right turn for each category. The data were collected from entry to exit. The steering angle values for roundabout in summer and in winter are greater than those for the other at-grade intersections, except for those for the non-signalized intersection. The steering angle values for roundabout are greater than those for rotary, which has the similar circular roadway as that of the roundabout.

For winter, when the road surface is slippery, multiple comparisons were done between the average values for the roundabout and those for the other intersections (Table 6). The comparisons found significant differences between the values for the roundabout and those for the signalized intersection (red and green lights) and for the rotary.

Table 5. Steering wheel angle per 1m travel distance (right turn)

(°/m)

Intersection type	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
Summer	7.3	7.3	13.9	23.0	18.6	19.2	5.0
Winter	9.3	8.4	20.9	19.3	23.3	22.7	3.9

Table 6. Comparisons between the intersection categories:
Test result for steering wheel angle (right turn) per 1m travel distance in winter

VS.	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
RAB Follow	0.000 *	0.000 *	0.984	0.451	-	1.000	0.000 *
RAB Single	0.001 *	0.001 *	1.000	0.973	1.000	-	0.000 *

Table 7 shows the average number of foot movements between the pedals, counted from entry to exit for the right turn at each intersection. The numbers of foot movements between the pedals for the roundabout in summer are about the same as those for the other intersections, and those in winter are greater than those for the signalized and non-signalized intersections.

Multiple comparisons were also done for the numbers of foot movements between the pedals at the roundabout and at the other intersections in winter (Table 8). The results show that the values for the roundabout differ from the values for the other at-grade intersections, except for those for the rotary.

Table 7. Number of foot movements between the pedals (right turn)

(Frequency)

Intersection type	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
Summer	1.8	1.1	1.0	1.8	1.8	1.8	3.3
Winter	1.6	2.1	1.6	1.8	4.1	5.0	4.8

Table 8. Comparison between the intersection categories:
Number of foot movements between the pedals (right turn) in winter

VS.	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
RAB Follow	0.000 *	0.011 *	0.000 *	0.003 *	-	0.996	0.990
RAB Single	0.007 *	0.027 *	0.008 *	0.012 *	0.996	-	1.000

3. 3. Vehicle Speed and Lateral Acceleration

Figure 6 shows the analysis results for vehicle average speed from entry to exit at right turn in each intersection. The average speed for the roundabout is lower than those for the other intersections both in summer and winter, and the variance in average speed by test subject is extremely low. Unlike the four-leg intersections, which show variations between the patterns of entry, the roundabout shows little difference between the values for the two patterns of entries in the same season.

Multiple comparisons between the average driving speed in winter for the roundabout and those for other intersections were also done (Table 9). Differences were found between the values for the roundabout and those for the signalized intersection (green light) and the rotary. It was found that the driving speed in the roundabout tended to be lower than that in the signalized intersection, because the values for the signalized intersection (red light) are close to 0.05, which is the threshold for determining significance.

The analysis results for lateral acceleration at right turn in each intersection show that the values for the roundabout are lower than those for the other at-grade intersections both in summer and winter, particularly in winter, and there is little variance by driver (Figure 7).

Multiple comparisons were also done for the average lateral acceleration in winter between the roundabout and the other intersections (Table 10). Differences were recognized between the values for the roundabout and those for the signalized (green) and non-signalized (major) intersections.

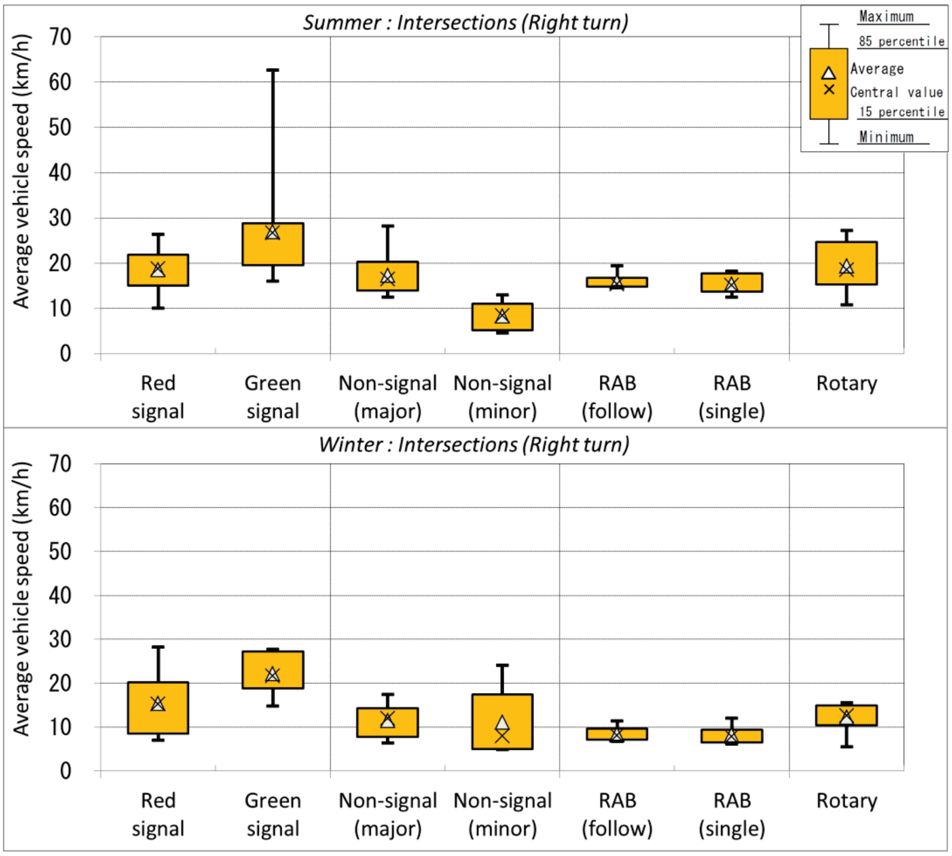

Figure 6. Average vehicle speed in the intersection (right turn)

Table 9. Comparison by intersection type:
Results of multiple comparisons for average vehicle speed in winter (right turn)

VS.	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
RAB Follow	0.060	0.000 *	0.345	0.998	-	1.000	0.054
RAB Single	0.053	0.000 *	0.314	0.996	1.000	-	0.048 *

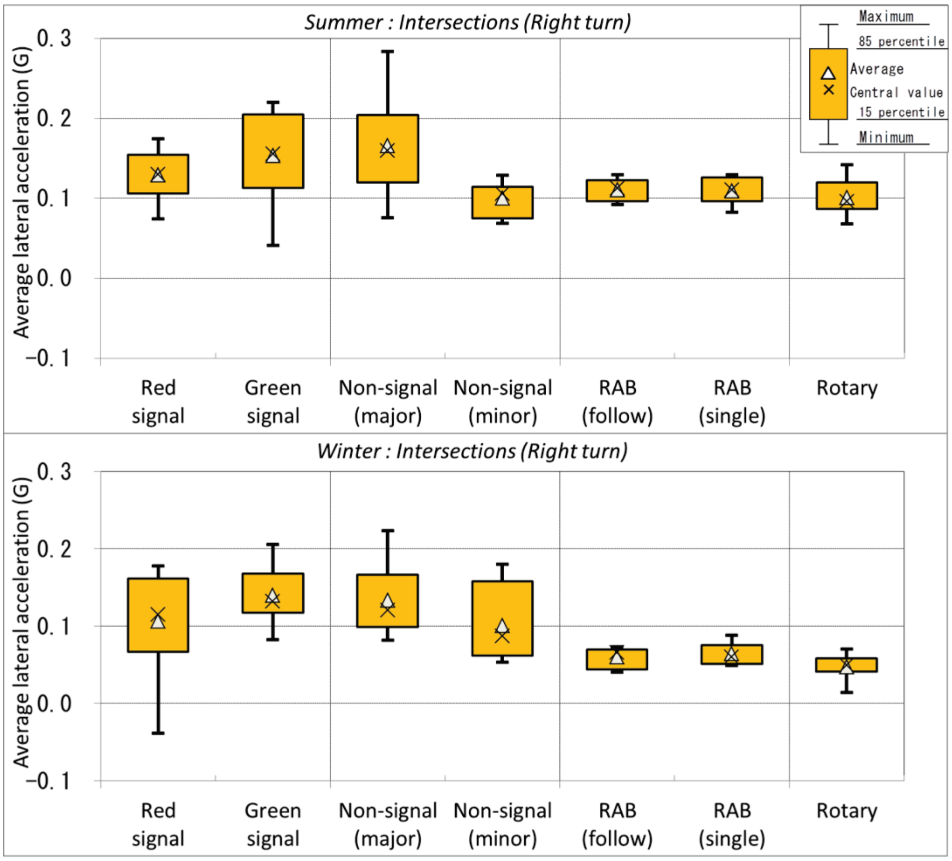

Figure 7. Average lateral acceleration in the intersection (right turn)

Table 10. Comparison between the intersections:
Results of multiple comparisons for average lateral acceleration in winter (right turn)

VS.	Signalized		Non-signalized		Roundabout		Rotary
	Red signal	Green signal	Major	Minor	Follow	Single	
RAB Follow	0.367	0.007 *	0.006 *	0.363	-	1.000	0.696
RAB Single	0.507	0.010 *	0.009 *	0.519	1.000	-	0.301

3. 4. Results of the Questionnaire Survey

In the questionnaire survey that was done after the driving test at each intersection, the drivers answers that, for both summer and winter, it was easier to confirm safety during right turn at the roundabout than at the non-signalized intersection. The driver evaluations of the roundabout were slightly more favorable than those of the signalized intersection (Figure 8).

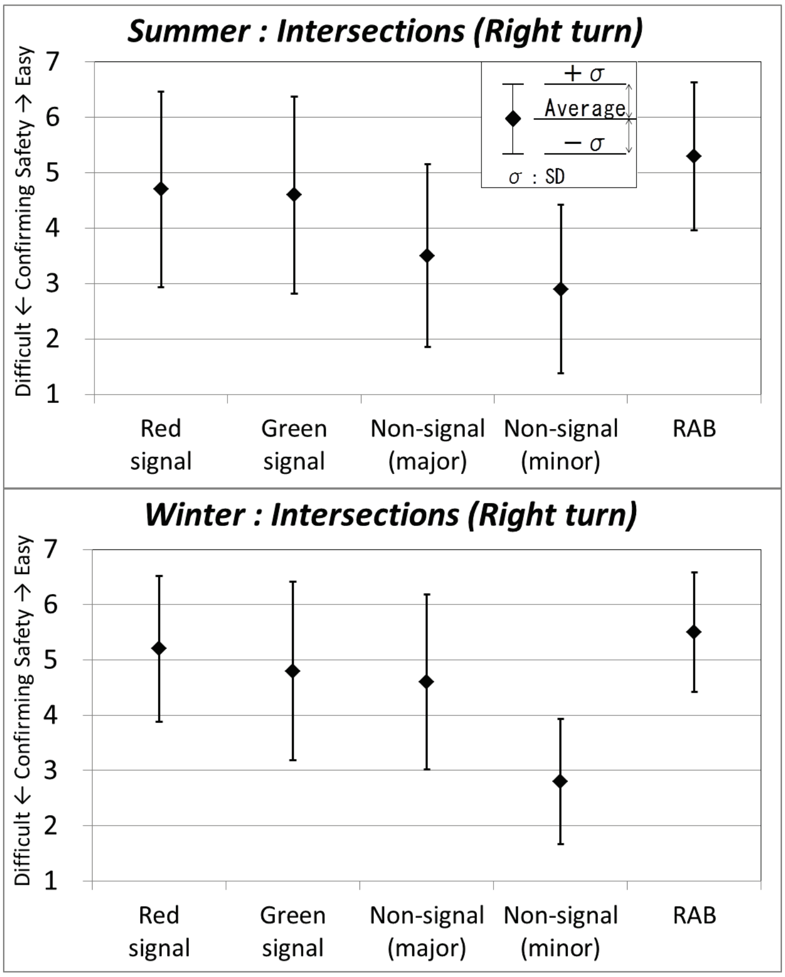

Figure 8. Ease in confirming safety (right turn)

4. DISCUSSION

The speeds of head movements upon entering the roundabout were about the same as those at the other intersections or lower. This is because when entering the roundabout, whose circular roadway has one-way clockwise traffic, safety confirmation can be done by checking only the right direction, whereas at the other types of intersections, safety confirmation is done by repeatedly looking right and left. It was not necessary to quickly move the head upon entry. It was found from the high scores in the questionnaire survey on safety confirmation that the roundabout is an intersection in which safety confirmation is easy both in summer and winter.

For steering wheel operation, the values for the roundabout were greater than those for the other types of intersections, because it is necessary to turn the steering wheel when driving on the circulatory roadway and turn it back at the exit, which made the turning angle greater than those for the other types of intersections. There were differences in steering wheel angles between the two types of at-grade, four-leg intersections, and these are thought to be because the non-signalized intersection was smaller than the signalized intersection and required a tighter turning radius. The reason for the greater steering wheel angle for the roundabout than for the rotary was that the outer diameter of the circulatory roadway of the roundabout was smaller than that of the rotary and required greater steering wheel angles. For pedal operation, the number of pedal operations at the roundabout in summer was about the same as at the at-grade four-leg intersections; however, the number of pedal operations in winter differed from those for the other at-grade, four-leg intersections. This was thought to be because driving on the circulatory roadway with a compacted snow surface required more frequent brake and accelerator pedal operations than driving in the four-leg intersections.

With respect to vehicle speed, the roundabout showed greater effect than the other types of intersections showed, which characterized the roundabout. It was also found that the roundabout had a more notable effect on vehicle speed than the signalized intersection had, and that the effect was found to be persist even in winter when the road surface condition is changeable. The difference between the vehicle speed for roundabout and rotary was the result of differences in the structure of the two intersections. On the rotary, this has a greater outer diameter and circulatory roadway width than those of the roundabout, the drivers tended to drive faster than on the roundabout. The values of data for lateral acceleration were smaller and less dispersed for the roundabout than those for at-grade, four-leg intersections. Based on the analysis results for vehicle speed, steering wheel angle and lateral acceleration, it is thought that the roundabout has a structure that promotes stable operation of the steering wheel and moderation of the vehicle speed, even though the steering wheel angle tends to be greater than that for the other structures.

The comparison between driving behavior on the roundabout in summer and winter revealed that the speed of the driver's head movement and the number of pedal operations were greater in winter than summer. This is thought to be because the snowy winter road surface is more slippery than the snow-free summer road surface, and because the road marker lines are invisible in winter. Unlike at other at-grade intersections, the experimental roundabout installed on the test road had very few objects for marking the roadway, including delineators and buildings, which resulted in the fast movement of the driver's head and frequent use of the brake and accelerator pedals (Photo 5).

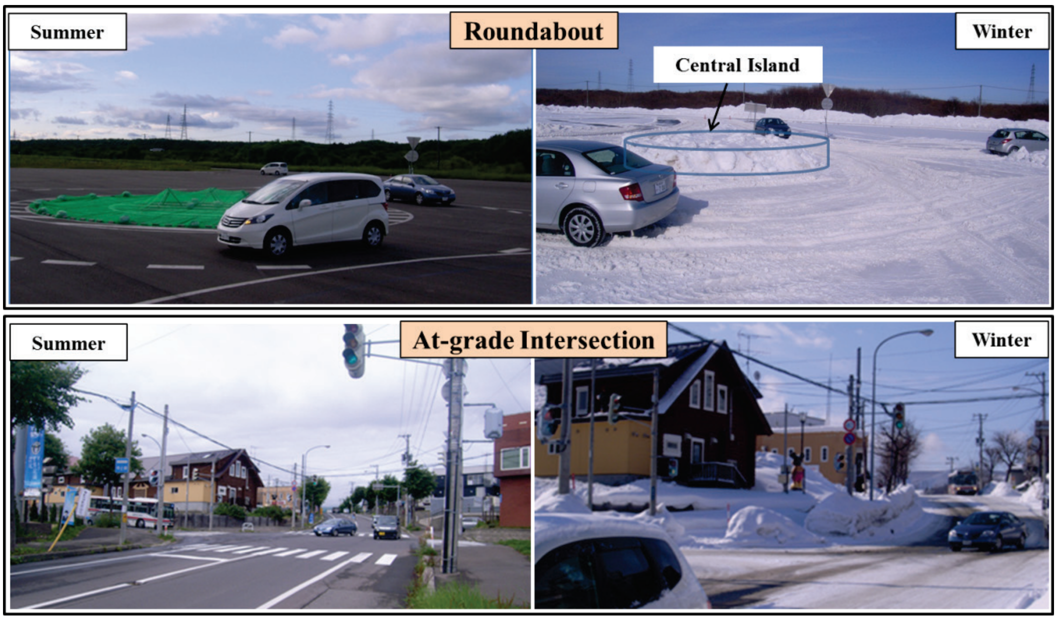

Photo 5. The condition of the driving test in summer and winter

5. Summary

The followings are the findings of this study.

(1) In both summer and winter, driving on the roundabout requires head movements that are no faster than those for the other types of intersections. In addition, the data for roundabout had smaller dispersion among the test subjects than those data for the other intersections, and from the results of the questionnaire survey on safety confirmation behaviors, it can be said that the roundabout is a type of intersection in which safety confirmation can be done easily even under snowy conditions.

(2) Based on the low driving speed, the small variation in speed by subject and the results of analysis for lateral acceleration, it was found that the stability of the vehicle at the roundabout is about as good as, or better than, those at the at-grade, four-leg intersections, even in winter. Based on the above discussion we consider that the roundabout has low susceptibility for serious accidents even under snow cover conditions and is a very safe structure.

(3) The comparison between the roundabout and the rotary also revealed that it is important to consider the structural configuration, such as the outer diameter and width of the circulatory roadway, in order for the roundabout to exhibit its effect of moderating travel speed.

(4) On the roundabout in winter, it is necessary to make it easier for drivers to know the location of their vehicle, because the speed and distance of head movement, the steering wheel angle and the number of pedal operations tend to be higher in winter than in summer.

To make safety confirmation easier even in winter, delineators such as snow poles will be installed at the center island and at entrances and exits of the circular roadway in future experiments. The installation of safety facilities will take winter maintenance into consideration. The effect of such safety measures for clarifying the vehicle driving location will be quantitatively measured. Elements such as traffic volume and pedestrians will be examined by conducting experiments under conditions that are closer to those of actual roads. The introduction of roundabouts in cold snowy regions will be examined through driving experiments under various winter road conditions.

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