MECHANICAL ENGINEERING | RESEARCH ARTICLE

Safety analysis of roundabouts and avoidance of conflicts for intersection-advanced driver assistance systems

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Abstract: In this paper, the results of safety analysis in roundabouts, unsignalized intersections, which are widely spread, and practical methods to avoid collision accidents or conflicts are presented. First, possible collision types (scenarios) were distinguished in roundabout with recent accident data and safety characteristics for three roundabouts of different structures were analyzed using video image processing methods. Through the analysis process, conflict events were identified one by one to classify criteria, and a method for evaluating the safety of the target roundabout was proposed. In addition, a self-driving method based on a car-mounted (black box) camera was proposed. This may be applicable to the implementation of Intersection-Advanced Driver Assistance System (I-ADAS) by providing the driver with safety-related information regarding entry into the roundabout.

Subjects: Automotive Design; Automotive Technology & Engineering; Intelligent & Automated Transport System Technology; Transportation Engineering

Keywords: roundabouts; safety; conflicts; collision accidents; car-mounted camera; advanced driver assistance systems

1. Introduction
Roundabout, which is spreading all over the world due to the advantages of low maintenance cost, smooth traffic flow, and safe operation, is a kind of flat intersection that rotates around the round traffic island in the center of the intersection without traffic lights and passes through the intersection. The basic principle is to yield to a car driving on a roundabout inside the intersection. However, as the number of roundabouts increases, various roundabouts are constructed according to the conditions of surrounding roads, and special types of accidents caused by inexperienced drivers at roundabouts are also increasing. For beginner driving, that is, early

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autonomous driving and Advanced Driver Assistance System (ADAS), more difficulties can be exacerbated than in the case of a four-way intersection. In addition, as the diameter of the central transportation island is reduced and traffic volume increases due to space constraints, collision accidents are increasing, which leads to a reduction in speed, which impedes smooth traffic flow.

Roundabouts, which are unsignalized, have very different traffic and collision types from normal signal-type intersections. The Virginia Tech Transportation Institute (2019) built a database (DB) that includes near-accident video and quantitative data from intersections received from the vision and radar sensors of vehicles driven by research participants from October 2010 to December 2013. This DB has most of the four-way intersection data, but also contains a considerable amount of roundabout near accident data. The traditional safety analysis of roundabout has relied on statistical analysis of accumulated collision accident data, but recently, there have been efforts to obtain a solution to the roundabout safety problem by analyzing videos shot for a long time. Sadeq and Sayed (2016) and Osama et al. (2016) used video to classify the types of conflict (near-collision accidents) that may occur in roundabout, and based on this, presented tools and case studies that automatically analyze the safety of roundabout. L. A. Bulla-Cruz et al. (2020) extended the conflict-based safety assessment to a microscopic risk assessment, and L. Bulla-Cruz et al. (2021) proposed a multivariate approach of surrogate safety measures for conflict-based safety assessment. Balado et al. (2019) performed a safety analysis of roundabouts and turbo roundabouts based on Petri nets and proved that Petri nets are perfectly applicable to measure the complexity and security of the system. Orsini et al. (2019) presented the application of extreme value theory for estimating the risk to be involved in an entering-circulating collision in single-lane roundabouts.

Since the roundabout is the unsignalized type, in the autonomous driving method, unlike a signal-type intersection, the importance of artificial intelligence based on any rules or empirical rules becomes greater. Rastelli and Peñas (2015) studied steering control based on Fuzzy logic for roundabout autonomous driving. Tian et al. (2018) proposed a roundabout autonomous driving algorithm based on a game-theoretic model that represents the interaction between a vehicle and an opponent vehicle. Rodrigues et al. (2018) also collected a driver’s roundabout driving style and vehicle status and analyzed situations that seemed to occur and how to cope with them, and conducted a study to utilize them for autonomous driving. In this way, for the development of roundabout autonomous driving or ADAS, it is very important to study the characteristic analysis of the vehicle collision situation that may or may not occur in roundabout. In addition, it is possible to supplement the design and construction related to autonomous driving by performing an appropriate safety evaluation of the unsignalized roundabout.

This study was conducted in two stages. First, possible collision types (scenarios) were distinguished in roundabout and related characteristics were analyzed. In addition to the roundabout safety evaluation method, a collision avoidance driving method was presented.

2. Status and types of accidents/conflicts on roundabouts

From 2015 to 2018, based on the database (Korean National Police Agency, 2019) in Korea in the past four years, the number of traffic accidents increased from 783 cases in 2015 to annually and reached 1051 cases in 2018. In the form of accidents, vehicle-to-vehicle accidents are the most common at 80%, most of them are front-to-side collisions, followed by front-to-rear collisions. In addition, although the ratio is small, it is estimated that the single vehicle accident and the vehicle-to-person accident are related to the road departure of the vehicle and the structure of the roundabout.

Virginia Tech Transportation Institute (2019) has a total of 3370 vehicles from October 2010 to December 2013, driving in six states (Florida, Indiana, New York, North Carolina,
Pennsylvania, Washington). They have built a database (SHRP2 Data) that contains the conflict image and quantitative data at the intersection received from the vision sensor and radar sensor. Roundabout-related data in the VTTI database (DB) are limited to near-accidents or conflict cases (Hydén, 1987). The difference between a vehicle conflict and an accident depends on whether the vehicle collides. In a conflict, the driver of the vehicle recognizes the dangerous situation before the accident occurs and does not lead to an actual collision accident by performing appropriate avoidance actions such as stopping or steering. However, even if there is no direct human or property damage like an actual accident, the conflict should be reduced because it creates traffic jams or uncertain traffic conditions and causes other traffic accidents. Therefore, the conflict event becomes an important indicator in addition to the actual accident in evaluating the safety of roundabout (Sadeq & Sayed, 2016). Moreover, because the number of accidents in a particular roundabout may be small enough to make an adequate safety assessment despite a long-term investigation, it is more important to analyze the type and frequency of conflict events. In addition, to develop autonomous driving or effective ADAS at the roundabout as well as at the four-way intersection (Han, 2020, 2021; Scanlon et al., 2016), characterization of the conflict situation occurring in the roundabout is important.

In this study, by analyzing the roundabout conflict data in Korea’s roundabout accident data and VTTI DB, possible collision accident types were divided into four types: one vehicle, vehicle-to-vehicle, sideswipe, and rear-end (Figure 1). The one vehicle collision shown in Figure 1(a) refers to the type of accident that occurs when a vehicle driving a roundabout collides with

![Figure 1. Types of possible collision accidents at roundabouts.](image-url)
a road structure or a fixed object around it. Unlike regular intersections, special structures such as central islands and splitters are essential in roundabout. The vehicle-to-vehicle collision in Figure 1(b) is defined as an accident in which one vehicle impacts the side of another vehicle. According to roundabout accident statistics in Korea (Korean National Police Agency, 2019), this is the most common type of event in roundabout. In this type, a turning vehicle impacts the left side of the entering vehicle or an entering vehicle impacts the right side of the turning vehicle. Sideswipe collision accident type is mainly driven in one direction in roundabout. It is a type in which two or more vehicles traveling in the same direction pass each other side parts. Unlike the general four-way intersection, many are found characteristically in the roundabout. Rear-end collision is a type of accident in which the front part of one vehicle collides with the rear part of another vehicle. Although not much was found in Korean roundabout accident data, several related conflicts occurred in VTTI DB. Unlike the four-way intersection, it is considered that there is no signal in the roundabout. It occurs a lot between the turning vehicle and the entering vehicle or between the vehicle trying to advance out of the roundabout and the following turning vehicle.

3. Safety evaluation of roundabouts through video analysis

For concrete accident type analysis and safety evaluation of the roundabout, three roundabouts of different structures located in and around Sejong City, the administrative city of Korea, were selected and video analysis was performed. The selection criteria were mainly roundabout, with relatively heavy traffic, and each had a different structure in the form of a single lane, double lane, and special shape.

In the roundabout, it is rare that vehicles are relatively slow to reach a collision accident, and it is not possible to secure enough accidents for analysis through long-time shooting. Therefore, rather than the actual collision accident, the purpose was to collect several conflict events that occurred in a short time on a roundabout. The traffic conflicts occur more frequently than collisions and are of little social cost (Ismail et al., 2009). The shooting was conducted for one hour each by selecting the time with the greatest amount of traffic on each roundabout. During shooting, no actual crash occurred at all three roundabouts.

The single lane roundabout is expected to have many collision-type accidents because there are public transportation stops around it, and traffic is complicated. In the double lane roundabout, there was a lot of traffic due to the presence of nearby tourist attractions, as well as a lot of driving vehicles unfamiliar with geography. In the special double lane roundabout, many sideswipe types are expected to occur, but due to the structure having a right turn lane separated from the driveway to the roundabout, the overall number of accidents was thought to be smaller than the normal double lane roundabout.

The way to avoid collision accidents, that is, the countermeasures taken by the driver in a collision accident situation, can be largely divided into two types: braking avoidance and steering avoidance (Han, 2020, 2021). In this study, three criteria were set based on these avoidance measures, that is, the driver’s countermeasures. The first conflict criterion is a sudden stop. This is a situation in which two or more vehicles suddenly stop, which may cause side collision and rear collision between vehicles. The second conflict criterion is lane departure. Due to the nature of the double lane roundabout, two vehicles traveling in a relatively wide lane often occur, and may cause sideswipe or side collision between vehicles. The third conflict criterion is avoidance. This is a situation in which a vehicle that is obstructed while driving in an intersection is driven while avoiding steering and may cause side collisions or secondary accidents with other vehicles. On the other hand, in the roundabout without traffic lights, it was confirmed that there are more cases where the horn sounds than the general intersection because the driving must proceed at the driver’s discretion. In the case of horn sound, it was judged as a situation of interest in image analysis, but it was not determined as a conflict.
The above three roundabout videos were analyzed, and conflict events were identified and classified. To classify the conflicts from the results of the image analysis, the sudden stop is indicated by a red circle, the lane departure is a green triangle, and the avoidance is a yellow diamond. Based on the results of this analysis, the safety of roundabouts was compared and evaluated.

As shown in the four-way single lane roundabout picture shown in Figure 2, 29 conflicts were confirmed in one hour. The most frequently applied conflict criterion was a sudden stop (red circle), accounting for 76%, followed by a lane departure (green triangle), which accounted for 21%. The conflict criteria of sudden stops and lane departures were mainly applied near the driveway of the roundabout. When classified into the types of collision accidents shown in Figure 1, vehicle-to-vehicle collision types accounted for 66% of conflicts, and rear-end and sideswipe were 17%, respectively. In the collision type of conflicts, the collision between the roundabout entering vehicle and the turning vehicle is mostly, and among them, the case where the turning vehicle impacts the entering vehicle is more than doubled. The rear-end collision type occurred mostly in the conflicts of sudden stop and avoidance (yellow diamond), and the side-spike type occurred in several lane departure conflicts. In single lane roundabout, unlike other types of roundabouts, most of the conflicts occurred except the sideswipe with a small frequency, which occurred near the driveway.

As shown in the picture of the four-way double lane roundabout shown in Figure 3, 43 conflicts were confirmed in one hour. The most conflict criterion was a sudden stop (red circle), accounting for 65%, followed by a lane departure (green triangle), accounting for 26%. The sudden stop conflict criterion shows the results evenly distributed throughout the roundabout. The conflict criterion of lane departure also occurred evenly throughout the roundabout. According to the collision accident type shown in Figure 1, the vehicle-to-vehicle collision type occupied 63%, and sideswipe 26% and rear-end 9% in the conflict. In the collision type of conflicts, the collision between the entering vehicle and the turning vehicle was mostly due to the rotating intersection, but unlike the single lane roundabout, the entering vehicle was more likely to impact the turning vehicle. The rear-end occurred at the emergency stop criterion, and the avoidance criterion only generated the collision type. Here, unlike single lane roundabout, several sideswipes occurred, and
only in the type of lane departure. In the double lane roundabout, unlike other types of roundabouts, the sudden stop criterion and the lane departure criterion occur evenly throughout the roundabout.

As shown in the special double lane roundabout (structure having a right turn lane separated from the driveway) in Figure 4, Figure 13 conflicts were confirmed in one hour. The most conflict criteria are sudden stops (red circles), which account for 61%, followed by lane departures (green triangles), which account for 30%. The overall number of cases is much less than that of other types of roundabouts, and most conflict criteria are relatively evenly distributed in roundabout. When classified by the type of collision shown in Figure 1, the collision type accounted for 46% of the conflicts, and the rear-end and sideswipe were 23%, respectively. Like the double lane roundabout, in the collision type of conflict, the number of impacts on vehicles with turning vehicles was slightly higher. However, the rear-end and sideswipe types showed a similar trend to the single lane roundabout rather than the double lane roundabout. Rear-end occurred mostly in the emergency stop and avoidance criteria, and sideswipe occurred in the lane departure criteria.

Table 1 summarizes the results of video-based safety analysis for three four-way roundabouts having different structures. Overwhelmingly many conflicts in all three roundabouts were based on a sudden stop criterion, followed by lane departures. Conflict points are evenly distributed throughout the roundabout including the driveway in the single lane roundabout and the driveway in the double lane roundabout, regardless of the criterion type. And, in the special double lane roundabout, much fewer conflicts were found than other types of roundabouts. This is understood as the effect of the structure having a right turn lane separated from the driveway.

| Table 1. Summary of video-based safety analysis results for roundabouts |
|--------------------------------------------------|-----------------|-----------------|-----------------|
| Number of conflicts                             | Single lane roundabout | Double lane roundabout | Special double lane roundabout |
| Conflicts criterion                             | 29               | 44               | 13               |
| Sudden stop                                     | 22               | 29               | 9                |
| Lane departure                                   | 6                | 11               | 4                |
| Avoidance                                       | 1                | 3                | 0                |
| Collision type                                   | Entering vehicle  | 6                | 15               | 4                |
| Turning vehicle                                  | 13               | 12               | 2                |
| Sideswipe                                        | 5                | 11               | 1                |
| Rear-end                                         | 5                | 4                | 3                |
| Conflict location                                | Entrance          | Entire            | Entire            |
On the other hand, according to the type of collision shown in Figure 1, the collision between the turning vehicle and the entering vehicle was the most frequent, and the driving of the entering vehicle was the most common reason. Therefore, it will be important to install a structure that guides the slowing of the entry vehicle. In particular, the sideswipe that occurred in several double lane roundabouts is mostly lane departure criterion in all three roundabouts. Due to the characteristics of roundabout, which has a somewhat wider width than general roads, it was confirmed that a situation in which more vehicles than the number of lanes temporarily travel together due to vehicles entering and exiting frequently occurs. To cope with this, the operation of a turbo-type roundabout (Lim & Choi, 2018) in which rotation or advance is designated for each lane may be effective.

4. Conflict avoidance and autonomous driving methods

In this study, through the analysis of various types of conflicts with single lane and double lane roundabout video images, the possible collision accidents and avoidance types in roundabout were identified. In addition, a vehicle-mounted camera-based method to properly utilize these analysis results for autonomous driving of roundabout is proposed.

4.1. Conflict analysis and avoidance at roundabouts

Figures 5–7 show the progress of the conflict of the collision, rear-end, and sideswipe accident types in a single lane roundabout, respectively. Drivers driving a single lane roundabout usually choose braking avoidance in conflict, and most types of collision and rear-end accidents except sideswipe occurred near the driveway. In Figure 5(a), the entering vehicle and the turning vehicle recognize the relative vehicle, and in (b) the vehicle behavior is controlled according to the movement of the relative vehicle. In (c), the entering vehicle ultimately enters, and the turning vehicle selects the action of the sudden stop. Subsequently, rear-end accident types, as shown in Figure 6, may occur continuously. Therefore, the entering vehicle must stop if the roundabout turning vehicle is in sight as soon as it enters the driveway. On the other hand, in
Figure 7(a), the vehicle behind the truck is trying to get out of the roundabout, but as shown in (b), it does not escape, but instead runs roundabout. Here, the preceding vehicle, the truck, decelerates due to other vehicles entering, and thus, a conflict in the type of sideswipe accident occurs in (c).

Figures 8–10 show the conflict situation of the collision, rear-end, and sideswipe in the double lane roundabout, respectively. Even in the double lane roundabout, there were many sudden stops in conflict criterion, and some avoidances were made. Therefore, the driver usually chooses braking avoidance, but steering avoidance can also be seen. Unlike the single lane, the conflict occurrence point is evenly distributed throughout the roundabout including the driveway. As can be seen in Figure 8, in the double lane roundabout, the decision to enter can be bold, so the probability of an accident in which an entering vehicle impacts a turning vehicle is greater than a single lane. In addition, collision avoidance between vehicles driving in the roundabout becomes important. In the double lane roundabout, unlike the single lane, multiple sideswipes occur, and usually have a lane departure form. This also occurs between driving vehicles due to excessive lane changes of vehicles attempting to exit the roundabout. In Figure 10(a), two vehicles are shown driving roundabout, and another one is entering. In (b), three vehicles are driving in two lanes because the newly entered vehicle attempts an excessive change to the outside lane to try to advance immediately. In (c), as three vehicles run side by side, a conflict of sideswipe accident types appears. In this situation, a vehicle attempting to exit the roundabout will decide to stop or change lanes. Stopping causes the rear-end type of accident, as shown in Figure 9, and lane changes are likely to cause the sideswipe type of accident. Therefore, when changing lanes, additional time must be secured either before a sufficient time or by adding one turn.
Figure 11. Setting division for autonomous driving on roundabout.

4.2. Autonomous driving based on a vehicle-mounted camera

In both single lane and double lane roundabouts, there was the most collision-type conflict, followed by sideswipe and rear-end types. Collisions and rear-end types usually occurred near the driveway, and sideswipe occurred mainly on the inside and exit of the roundabout. Collision and rear-end accident types were mostly caused by the conflict between the entering vehicle and the turning vehicle. By comparing the qualitative speed and position values of the two vehicles, it is possible to determine whether to enter the roundabout and enable safe driving. Sideswipe conflict occurs mainly inside the double lane roundabout. To prevent this, the inside lane or the outside lane of the roundabout should be selected before entering the roundabout in consideration of the route exiting the roundabout.

When the vehicle enters at the south of the roundabout, which rotates counterclockwise from the right traffic reference, as shown in Figure 11, the risk of entry of the roundabout can be determined based on the location and speed of the turning vehicle. If the turning vehicle is in a red zone, it is considered an entry hazard, and if it is in a yellow zone, it is considered an entry caution. The entry hazard is actually a decision not to enter, but the entry caution is to decide whether to enter in consideration of the speed of the driving vehicle.

Figure 11 shows the video image taken from the front using a black box camera (Han, 2016) of a vehicle entering a single lane roundabout. To qualitatively check the existence of a vehicle driving roundabout in the vicinity, the screen is divided into three sections and analyzed in real time. Here, the number and size of divisions of sections can be changed. If the vehicle is recognized in the first and second sections of the image, it is determined that there are other vehicles in the Warning (yellow) and Danger (red) areas, respectively. In the third area, the right half, if a vehicle is recognized, it may still be considered a risk. The presence (O) or absence (X) of a vehicle in each divided section of the image serves to determine whether the vehicle enters. It may be different depending on the driving mode, but if the presence of the vehicle is confirmed in any one of the three sections shown in the image in Figure 11, it will be a safe mode to stop the entry vehicle. This is more like an ordinary driver’s driving style than a method of determining whether to enter by estimating a quantitative speed of a relative vehicle or a vehicle with various sensors.
In this study, the roundabout ADAS works in the section passing through the separated traffic island installed in the roundabout driveway. A qualitative judgment (Han, 2018) was made about the entry of the roundabout through analysis of the camera image at the start and end points of the traffic splitter. As shown in Figure 12, the situation in which safe entry to the roundabout is possible is limited to the seven combinations of judgments at these two points. In other combinations, the vehicle first stops and then waits for a change in situation or it is impossible to occur. These qualitative rules were verified through PC-Crash (2022) simulation analysis as shown in Figure 12, and the possibility was confirmed through actual vehicle experiments at roundabout. As shown in Figures 13 and 14, the OPENCV program was used as a tool for image analysis. Here, presence or absence of a vehicle in each divided section (1, 2, 3) of the image is represented by “O” or “X”, respectively.

Figure 12. PC-Crash simulation analysis results for constructing qualitative rules.
Figure 12. (continued).
In real-vehicle experiments, a GO signal comes out in Figure 13(a) and the vehicle is allowed to enter. However, it immediately detects a vehicle rotating in Section 1 of the camera image and stops the vehicle by generating a STOP signal as shown in Figure 13(b). Subsequently, after a considerable number of vehicles rotate, as shown in Figure 13(c), the experimental vehicle receives a GO signal and enters the roundabout.

In Figure 14(a), a STOP signal is generated after the experimental vehicle entering the roundabout and the turning vehicle is recognized in Section 1 of the camera image. Even in the situation Figure 14(b), there is no vehicle in Section 1, but a vehicle in Section 2 is recognized and a STOP signal is generated. Then, in the situation Figure 14(c), there was no vehicle rotating in Sections 1 and 2 of the camera images, and a GO signal was generated and entered. Most of the errors occurred when several vehicles existed on a roundabout, GO and STOP signals alternately repeated, and supplementation would be possible.

5. Conclusions
In this study, by analyzing the roundabout accident data in Korea over the past 4 years and the roundabout conflict data in the VTTI DB, possible collision accidents were classified into four types: vehicle-to-vehicle collision, rear-end, sideswipe, and one vehicle. For concrete accident-type analysis and safety evaluation of roundabout, three roundabouts of different structures were selected, and video analysis was performed. Through this analysis process, conflicting events were specified individually to classify criteria, and a method for evaluating the safety of the target roundabout was proposed. The criteria for judging conflict in video analysis were set as three: sudden stop, lane departure, and avoidance based on the driver’s countermeasures.

Through various types of conflict analysis with single lane and double lane roundabout images, actual possible accidents and avoidance types were identified in roundabout. Using these roundabout video analysis results, a self-driving method based on a black box camera was proposed. This is applicable to the implementation of Intersection-ADAS by providing the driver with safety-related information regarding entry into the roundabout.

Since the roundabout is the unsignalized type, the importance of the autonomous driving based on empirical rules increases even further. In actual autonomous driving videos that can be found, it is often seen from the entry point of the roundabout waiting indefinitely until no vehicles are seen throughout the roundabout. However, it is considered still difficult to apply the proposed method to fully autonomous driving. The qualitative algorithm developed in this study includes several situations that cannot but be left to the driver’s decision. Therefore, it is currently considered suitable and applicable to ADAS.
Funding
This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2019R1I1A3A01057373).

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Disclosure statement
No potential conflict of interest was reported by the author(s).

Citation information
Cite this article as: Safety analysis of roundabouts and avoidance of conflicts for intersection-advanced driver assistance systems, Inhan Han, Cogent Engineering (2022), 9: 2112813.

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