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Experimental analysis of pedestrian behavior at different configurations of crosswalks at roundabout legs

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Abstract

Walking has recently been one of the most popular forms of mobility proposed in many urban plans and in the new concept of sustainable mobility. This study investigated pedestrian behavior when crossing the legs of urban roundabouts. Pedestrian crossing behavior was analyzed using video recordings made at seven crosswalks located on urban roundabouts. To describe pedestrian behavior, crossing conditions (legal or illegal) and Kerb Delay were chosen.

The data obtained from the video analysis were treated with CHAID analysis to determine the distribution of the parameters chosen as a function of features considered more conditioning. A path analysis was then performed to assess the influence of these features on the parameters defining pedestrian behavior.

In order to encourage legal pedestrian behavior, the results of the present study suggest implementation of refuge islands at the legs of roundabouts. The research results can help refine the algorithms that define autonomous vehicle-pedestrian interactions.

Keywords: Kerb Delay, crossing condition, vulnerable users, pedestrian crossing maneuvers, road safety.

1. Introduction

The increase of pedestrian mobility and studies related to urban spaces to facilitate accessibility and walkability is the main strategy for the development smart and green of cities. Walking has recently been one of the most popular forms of mobility proposed in many urban plans and in the new concept of sustainable mobility. Unfortunately, infrastructure, in urban areas are not always designed with the needs of pedestrians in mind, but are often designed with the vehicle drivers in mind only, which can lead to long waits for pedestrians, resulting in unsafe maneuvers. Crossing the road can be considered a challenging and demanding task, as it requires multiple processes, decisions and actions that must be executed quickly. Crossing the road requires pedestrians to trade off saving time against the likelihood of a collision. In urban areas, pedestrians often have to cross

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at intersections. In order to reduce the mutual interference between pedestrians and motor vehicles, crosswalks are usually set at intersections. The number of fatalities among people crossing an intersection is steadily increasing year by year (Xu et al., 2019; Soathong et al., 2019; Olszewski et al., 2015). Therefore, more attention should be paid to pedestrian safety, who crossing at intersection.

Nowadays, roundabouts are often built-in urban areas as well, in order to increase the safety and functionality of road traffic and reduce speed (Šurdonja et al., 2012, Hydén and Várhelyi, 2000). Studies related to roundabout safety have generally focused on drivers, overlooking the importance of the safety of vulnerable road users, such as pedestrians and cyclists (Zubaidi et al., 2020; Distefano et al., 2019; Leonardi et al., 2019).

A good understanding of pedestrian crossing behavior under mixed traffic conditions is necessary to provide the adequate infrastructure to improve pedestrian safety, especially at intersections. Analyzing of pedestrian crossing behavior in urban areas can help understand the way pedestrians interact with the street and the traffic environment. It can also help to understand how they balance the need for comfort and safety at the expense of delay within existing traffic rules. Recent studies have shown the importance of proper design of pedestrian crossings at intersections (Tang et al., 2020; Canale et al., 2015).

There are many studies on exploring the behaviors of pedestrians crossing the road at signalized (Pratelli et al., 2019; Koh, et al., 2014) and unsignalized intersections (Jain et al., 2014; Sahani et al, 2018), indeed the literature analyzing pedestrian behavior at roundabouts is still scarce (Perdomo et al., 2014; Vignali et al., 2020). Therefore, there is a need for comprehensive studies that identify the factors that may influence pedestrians crossing behavior at roundabout.

This study investigated pedestrian behavior when crossing a leg of roundabout. Crossing behavior was analyzed using unobtrusive video recordings of road crossings by a sample of younger and older pedestrians at seven crosswalks located on the legs of a series of urban roundabouts. The crosswalks were selected to have different geometric features to test whether these features influence pedestrian behavior. First, an analysis of the number of legal/illegal crossings was conducted to understand what factors encourage pedestrians crossing condition (legal/illegal). Then, for the legal crossings, the video footage was processed to calculate a parameter called Kerb Delay, which indicates whether the pedestrian anticipates or delays the crossing maneuver. Finally, we examined whether this parameter was affected by the characteristics of the crosswalks.

2. Methodology

2.1 Survey sites

The survey sites were chosen in order to observe pedestrian crossings on the legs of urban roundabouts with different characteristics. The pedestrian crossings analyzed are 7, of which 3 with painted islands, 2 with raised islands and which act as a refuge for pedestrians and 2 with raised island where, however, the crossing is located outside the island (Fig. 1). All the crosswalks are placed on the legs of urban roundabouts located in the Metropolitan Area of Catania.

For each crosswalk, the following characteristics were recorded: the crosswalk distance from the circulatory roadway of the roundabout, the presence or absence of the refuge island, the length of the crosswalk and the type of street, corresponding to the leg of the roundabout, on which it is located. Table 1 shows the characteristics of each crosswalk. For crosswalks with an island of refuge, the length of the crossing is understood to be the distance between the sidewalk and the island, as the pedestrian crosses one vehicular flow at a time.

Figure 1: View of the sites studied.
Source: Authors.

Table 1: Characteristics of the survey sites.

Crosswalk	*Crosswalk distance (m)*	*Refuge island*	*Crosswalk length /m)*	*Type of street*
1	13	No	7,90	Secondary
2	18,50	No	17,00	Main
3	3,00	Yes	7,60* 9,20	Secondary
4	29,00	No	11,90	Main
5	11,50	No	7,00	Secondary
6	28,00	Yes	11,50* 8,90	Main
7	18,80	No	10,50	Main

* In the presence of a refuge island, 2 crossing lengths are considered.

2.2 Crossing behavior indicators

Among all the parameters used to describe the behavior of pedestrians, the crossing condition (legal or illegal) and the Kerb Delay were chosen in this study.

A pedestrian crossing maneuver is defined as illegal simply when the pedestrian crosses outside the crosswalk. Pedestrian crossing outside of a crosswalk is one of the most frequent misbehavior of pedestrians and can significantly affect traffic safety (Bella and Nobili, 2020). The type of crossing (legal/illegal) was defined for all observed pedestrian crossing maneuvers.

The Kerb Delay is defined as the time from the last vehicle passing when the pedestrian is already waiting to the pedestrian's first step on the street (Oxley et al., 1997). Therefore, the Kerb Delay value can be calculated only for pedestrians who have stopped on the kerb waiting for a vehicle to pass. Fig. 2 shows the graphical representation of this parameter.

The Kerb Delay can assume negative values if the pedestrian anticipates the crossing with respect to the passing vehicle or positive values otherwise.

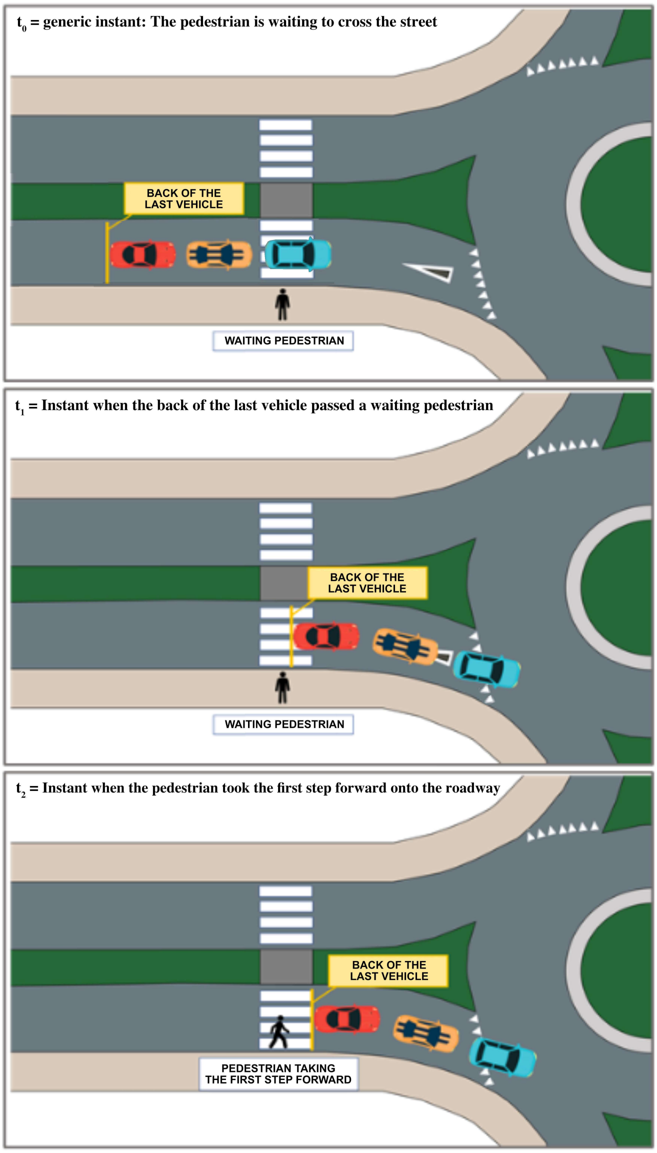

Figure 2: Graphical representation of Kerb Delay.
Source: Authors.

2.3 Data collection

Observations on the behavior of pedestrians in crossings on the branches of the roundabouts chosen as survey sites are indispensable in order to evaluate the two selected parameters. Video based data acquisition technique has been used for the purpose. A car parked near the crosswalk on the side of the road was set up with two video cameras positioned to provide images of both oncoming traffic and crossing pedestrians. The cameras were hidden into the car so that pedestrians could not see them. Filming occurred without pedestrian's knowledge to overcome possible changes in behavior. Video recordings were made for a total of 74 hours. The video recordings were made between 10:30 a.m. and 12:30 a.m. and between 3:30 and 5:30 p.m. on weekdays for eighteen days in September 2020 and in April 2021. The hourly intervals of the video recordings were chosen so that the vehicle flows and the approaching speeds were comparable on all sites studied. The video was played in Adobe Premiere Pro CS4 version 4.0.1 to perform a frame-by-frame analysis.

To study type of crossing, based on the videos analysis, 1270 pedestrian crossings were acquired in presence of refuge island and 1270 crossings in absence of refuge island. These were divided into legal and illegal crossings. For Kerb Delay only 680 pedestrian crossings (340 in presence of refuge island and 340 crossings in absence of it) were acquired for all crosswalk, because most of pedestrians observed did not stop to wait for a passing vehicle.

2.4 Analytical Methods

The data obtained from the video analysis were treated with CHAID (Chi-square Automatic Interaction Detector) analysis to determine the distribution of the parameters chosen to define the crossing behaviors (crossing condition and Kerb Delay) as a function of the defined items (crosswalk distance, crosswalk length, and street).

Subsequently, Path analysis was used to evaluate the influence of these aspects on the parameters defining pedestrian behavior.

CHAID analysis is a database segmentation technique useful for identifying relationships between categorical response variables. CHAID finds patterns in data that contain many categorical variables. After a test sequence, the data is subdivided using a statistical algorithm. CHAID analysis creates a prediction tree to determine how the variables best merge to explain the outcome of the given dependent variable. CHAID analysis can use nominal, ordinal, and continuous data, where continuous predictors are divided into categories with approximately equal numbers of observations.

The original node of the dependent variable is divided into two or more categories called the initial node or parent node. Then, using statistical algorithms, the nodes are divided into child nodes according to the variables that distinguish each of them. This process continues until no splits are significant. To determine optimal splits, the Chi-square test of independence is used to examine and test the cross-tabulations between each input variable (i.e., the independent variables) and the outcome variables (i.e., the dependent variable).

Path analysis is a statistical technique primarily used to examine the comparative strength of direct and indirect relationships between variables. The result is a model that identifies causal mechanisms by which independent variables have both direct and indirect effects on a dependent variable. Typically, path analysis involves the creation of a path diagram that specifically outlines the relationships among all variables and the causal direction between them. In a path diagram, arrows are used to show how different variables are related to each other. For example, an arrow pointing from variable A to variable B shows that variable A is likely to influence variable B. The single straight arrows indicate a causal relationship leading from the explanatory (causal) variable to the outcome (effect) variable. The curved double arrows indicate that the two variables may be related, but the model makes no prediction about the direction of the relationship.

Because path analysis assesses the comparative strength of different effects on an outcome, the relationships between variables in the path model are expressed in terms of correlations. Path models often report standardized regression coefficients (beta). Standardized coefficients allow researchers to compare the relative magnitude of the effects of different explanatory variables in the path model by adjusting the standard deviations so that all variables have the same standard deviation despite having different units of measurement. These standardized path coefficients measure the relative strength and sign of the effect from a causal variable to an endogenous variable.

The variables analyzed, in both analyzes, are shown in Table 2.

Table 2: Variables used in analytical methods.

Variable	Variable type	Categories
Crossing Condition	Dependent Variable	0=legal 1=illegal
Kerb Delay	Dependent Variable	A=< -1s B= -1s ÷ -0.5s C= -0.5s ÷ 0s D= 0 s÷ 0.5s E= 0.5s ÷ 1s F= >1s
Pedestrian	Independent Variable	0=Non elderly 1=Elderly
Refuge island	Independent Variable	0=Absent 1=Present
Crosswalk distance	Independent Variable	0=<10m 1= 10 m ÷ 15m 2=>15m
Crosswalk length	Independent Variable	0=<8m 1=8m ÷ 10m 2=>10m
Street	Independent Variable	0=Main 1=Secondary

3. Results and discussion

Figure 3 shows the tree diagram obtained for the CHAID analysis of Crossing condition.

The “Crossing condition” is divided into 7 subgroups by various branches connecting the root node to the leaf nodes. The splitting variables lead to the tree being divided into three levels. The structure of the tree foresees the crossing distance as the first (and therefore most significant) dividing variable.

From the analysis of Figure 3 it can be observed that the most frequent crossing condition is legal crossing. The percentage of legal condition at node 0 is indeed 79.9%.

This percentage assumes the maximum value for a crossing distance of more than 15 meters. In fact, the percentage of legal crossings on crosswalks that are more than 15 m from the entrance to the roundabout is 84.4% (node 1) compared to 58.1% for crossing distances between 10 m and 15 m (node 3). This suggests that users perceive a higher risk when the crosswalks are very far from the entry to the roundabout. This is probably due to the higher speeds of vehicles that have not yet reached the minimum speeds required for entry, whereas when exiting they have already reached the characteristic speeds of the road they entered.

The second level of the tree shows that in the case of crosswalks that are more than 15 m from the entrance line, elderly users respect the crossing rule on crosswalks (almost 88%) than non-elderly pedestrians (about 83%). This seems to indicate that older road users accept longer distances than younger ones to take advantage of crosswalks, thus prefer a higher level of safety overall.

The third level of the tree shows that the presence or absence of the pedestrian refuge island is only decisive for the behavioral decisions of the older users, who strongly tend to carry out the crossings in a legal way when the refuge island is present (about 83%). However, the tree shows that the percentage of elderly pedestrians who tend to cross legally in the absence of the refuge island is even higher (90%) than in the presence of the pedestrian refuge island. This can be explained by the very prudent behavior of elderly pedestrians who, faced with less safe crossing conditions (crosswalks at a greater distance from the entrance to the roundabout and lack of refuge islands), feel obliged to achieve the highest possible level of safety by using, to a very high percentage, the crosswalks on the legs of the roundabouts.

The path analysis was carried out in order to assess the strength of the links among exogenous and endogenous variables. According to the magnitude of direct effects, shown in the diagram of figure 4, the variables that most influence illegal pedestrian crossings are (in decreasing order of importance): “crosswalk length” (-0.18), presence of the “refuge island” (-0.15), type of “street” (0.07), type of “pedestrian” (-0.03), and “crosswalk distance” (-0.01). The type of “street” was found to be positively correlated with the “crossing conditions”. In contrast, “crosswalk length”, presence of the “refuge island”, type of “pedestrian” and “crosswalk distance” were inversely related to “crossing conditions”. It can be seen that none of the exogenous variables strongly influence the condition of legal / illegal crossings. However, it is clear that shorter crosswalks encourage illegal behavior, and furthermore, the absence of the refuge island seems to encourage pedestrians to cross legally. The path analysis result indicates that almost all the exogenous variables had indirect effects on these correlations in the model. Among these interactions, the combination of type of “street” and “crosswalk distance” had the largest impact of interaction (−0.76) on “crossing condition”, and the negative interaction indicated that there was a mutually restricted relationship between these two factors. The interaction between the type of "street" and the "crosswalk length" (-0.58) and that between the "crosswalk length" and the presence of the "refuge island" (-0.53) also had a significant effect on the "crossing condition"; these cases were also negative interactions, indicating mutually restricted relationships between the factors involved.

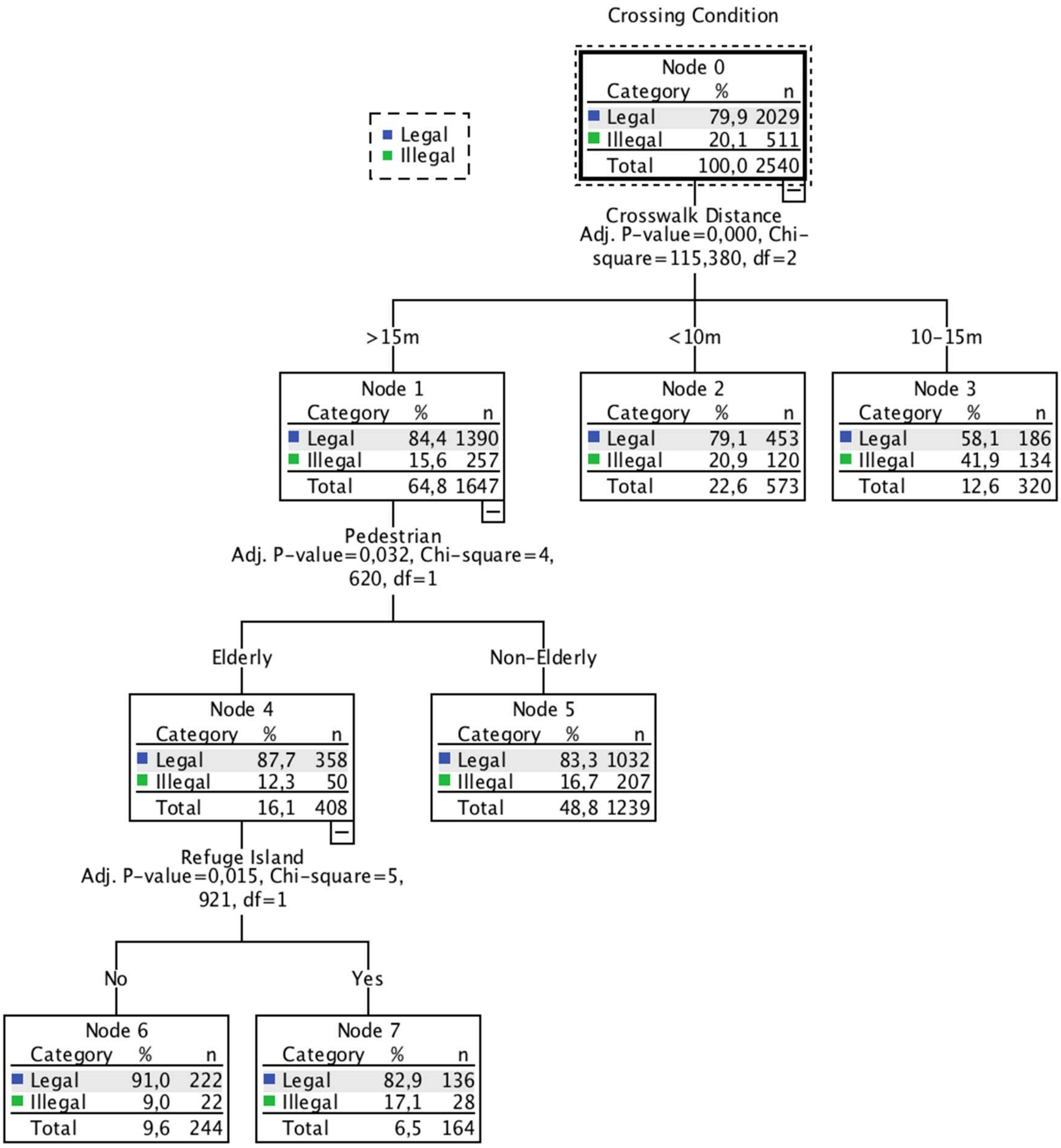

Figure 3: Crossing condition CHAID tree diagram.

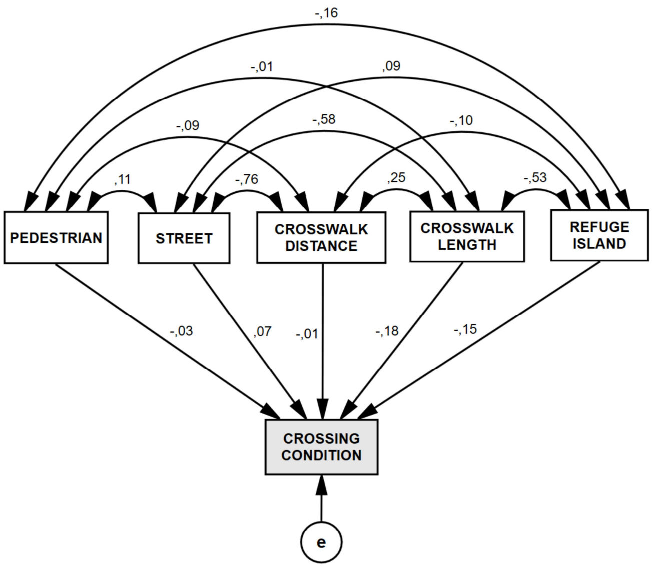

Figure 4: Crossing condition diagram of path analysis.

Figure 5 shows the tree diagram obtained for the CHAID analysis of Kerb Delay.

The “Kerb Delay” is divided into 12 subgroups by various branches connecting the root node to the leaf nodes. The splitting variables lead to the tree being divided into three levels.

The structure of the tree foresees the “presence of refuge island” as the first (and therefore most significant) dividing variable.

From the analysis of Figure 5 it can be observed that the most frequent Kerb Delay is B (i.e. -1s ÷ -0.5s). The percentage of negative values of Kerb Delay is 71.4% (A+B+C). This means that pedestrians tend to get off the sidewalk before the vehicle has entirely passed. This percentage increases to 79.10% (node 2) in the presence of a refuge island; in contrast, this percentage is 63.70% (node 2) for configurations without a refuge island. This result shows that all pedestrians feel safer in the presence of the refuge island and tend to anticipate the crossing maneuver; they are reinforced in this by the fact that the presence of the refuge island requires control of only one traffic flow at a time and crossing in two phases of crosswalks.

The second level of the tree shows how the variable "Crosswalk distance" is the dividing variable from both node 1 and node 2. With respect to the condition that there is no refuge island (node 1), the tree shows that the higher percentage of negative values of Kerb Delay (A+B+C = 83.40%) occurs when the crosswalk distance is less than 15 m, while when the crosswalk distance is more than 15 m, the above percentage is much lower (A+B+C = 53.10%). This means that in the absence of a refuge island, pedestrians only feel safer anticipating the crossing maneuver at crosswalks close to the entrance to the roundabout. Thus, pedestrians perceive a higher risk when the crosswalks are very far from the entrance to the roundabout. This is probably due, as said previously, to the higher speeds of vehicles in sites away from the roundabout. In the presence of a refuge island, the tree shows that the highest percentage of negative values of Kerb Delay (A+B+C = 84.60%) occurs when the crosswalk distance is less than 10 m. In contrast to the previous case (absence of the refuge island), the percentage of negative values of Kerb Delay is also quite high (A+B+C = 76.30%) when the crosswalk distance is more than 15m. It is thus evident that the presence of the refuge islands contributes to the pedestrians' confidence to anticipate the crossing maneuver in all conditions, even when the crosswalks are far from the roundabout entrance and are therefore characterized by vehicle flows traveling at a relatively high speed. The possibility of carrying out the pedestrian crossing in two phases, controlling one vehicle flow at a time, therefore encourages pedestrians to behave with particular determination and safety when crossing the legs of a roundabout.

The third level of the tree first shows how the variable "Pedestrian" is significant in determining the different values of the Kerb Delay associated with the "Crosswalk distance" conditions resulting from the absence of the refuge island. Specifically, in configurations where the crosswalk distance is greater than 15 m, non-elderly pedestrians are the ones who feel safer crossing the street and therefore generate the greatest percentage of negative values of Kerb Delay (A+B+C = 58.70%). Conversely, elderly pedestrians are less aggressive and more cautious than younger pedestrians, resulting in a very small percentage of negative values for Kerb Delay (A+B+C = 35.90%). When the crosswalk distance is less than 15 m, both categories of pedestrians show a clear tendency to anticipate the crossing maneuver. However, it is the non-elderly pedestrians who achieve a very high percentage of negative values of Kerb Delay (A+B+C = 98.30%). Older pedestrians, as usual, show greater caution, as shown by the percentage of negative values of Kerb Delay which, although significant (A+B+C = 68.30%), is well below the value of almost 100% typical of younger users.

The third level of the tree, secondly, shows that the variable "Crosswalk length" is significant in conditioning the values of Kerb Delay only because of the condition "Crosswalk distance"> 15 m, which results from the presence of the refuge island. Although it is not easy to explain the reasons for this, it can be noted that when the length of the crosswalk exceeds 10 m, the tendency to anticipate the crossing maneuver (A+B+C = 85.5%) is significantly stronger than in the configurations where the length of the crosswalk on the legs of the roundabouts is less than 10 m (A+B+C = 64.6%). It can be hypothesized that pedestrians are less willing to anticipate the crossing maneuver when the safety level of the crosswalk with the refuge island is also largely acceptable due to the short crosswalk length. It is likely that this condition does not encourage users to force the maneuver to begin the pedestrian crossing phase.

Again, path analysis was developed to assess the strength of the links between dependent and independent variables. According to the magnitude of the direct effects shown in the diagram in Figure 6, the variables that influence the Kerb Delay the most (in decreasing order of importance) are: “crosswalk distance” (0.27), presence of the “refuge island” (-0.19), “crosswalk length” (-0.13), type of “street” (-0.11), and type of “pedestrian” (0.10). The type of “pedestrian” and “crosswalk distance” were found to be positively correlated with the Kerb Delay. In contrast, type of “street”, “crosswalk length” and presence of the “refuge island” were inversely related to Kerb Delay. Note that only one of five variables (crosswalk distance) has a sufficiently strong influence on the values assumed by the Kerb Delay. The presence of the “refuge island” has a less strong relationship and the variables "crosswalk length", type of "street" and type of "pedestrian" have a very weak relationship with the values assumed by the Kerb Delay. In particular, it is evident that the tendency to delay the start of the crossing maneuver is a prerogative of configurations in which the crosswalks are particularly far from the entrance to the roundabout. The absence of the refuge island also favors the delayed start of the crossing maneuver for pedestrians.

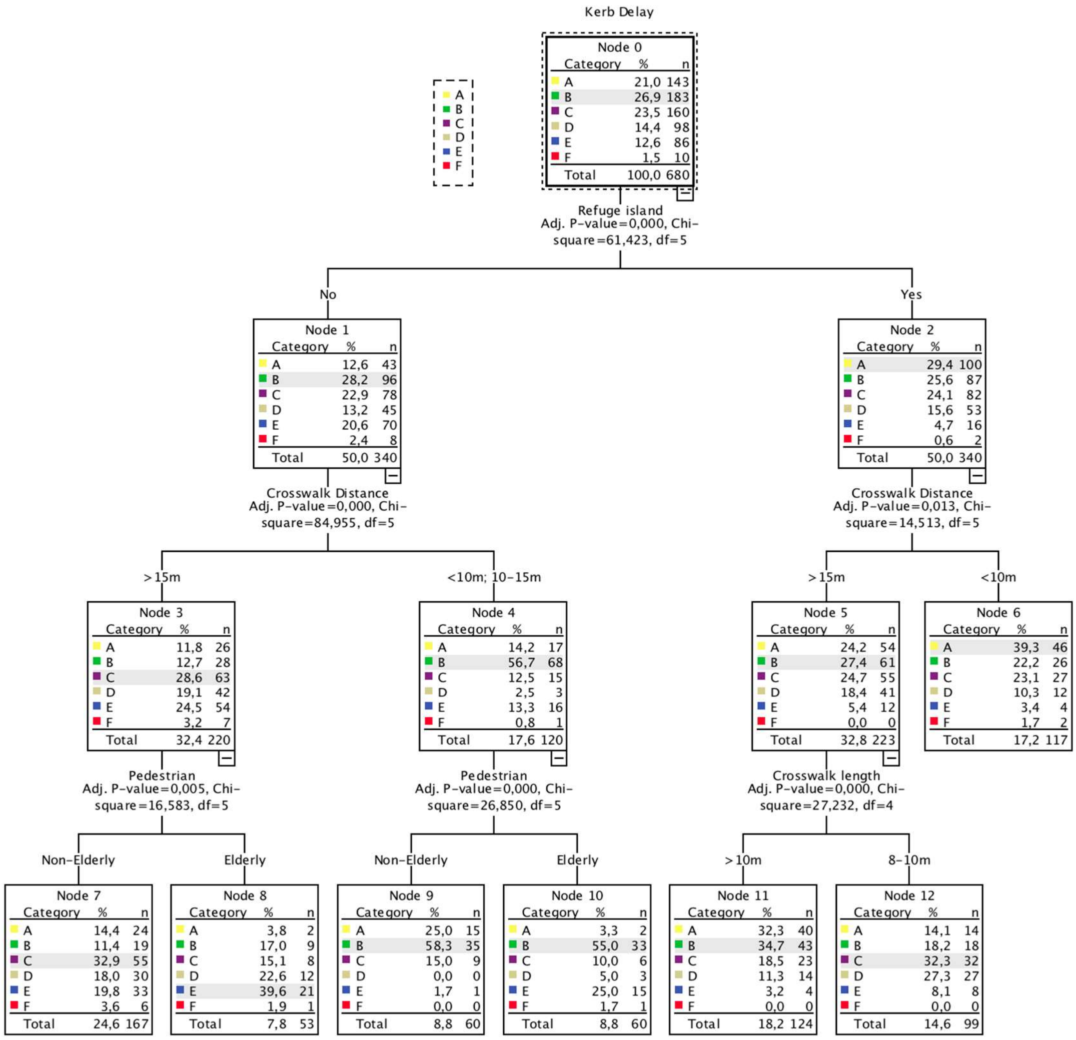

Figure 5: Kerb Delay CHAID tree diagram.

The path analysis result indicates that almost all the independent variables had indirect effects on these correlations in the model. Among these interactions, the combination of type of “street” and “crosswalk length” had the largest impact of interaction (−0.66) on Kerb Delay, and the negative interaction indicated that there was a mutually restricted relationship between these two factors. The interaction between "type of street" and "crosswalk distance" also has a noticeable effect on Kerb Delay and is negative (-0.48). The interaction between the "crosswalk distance" and the "crosswalk length" (0.52), and that between the type of "street" and the presence of the "refuge island" (0.43) also had a significant effect on the Kerb Delay; these cases were positive interactions, indicating mutually relationships between the factors involved.

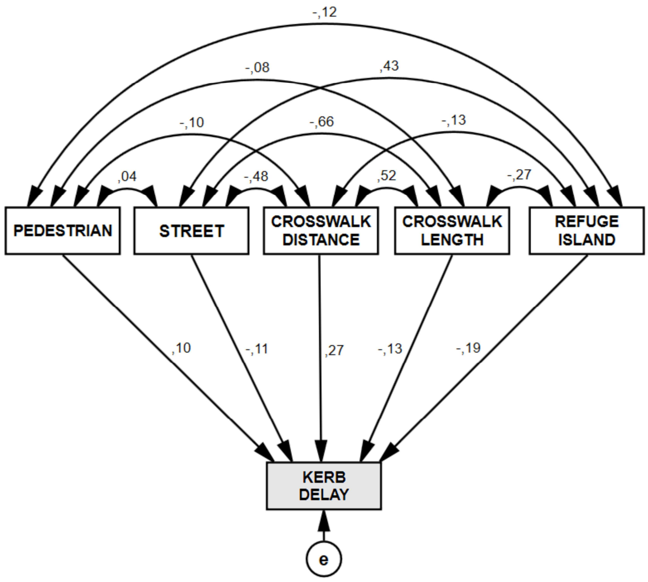

Figure 6. Kerb Delay diagram of path analysis.

The results of this study seem interesting for two reasons. First, it was possible to show the differences in behavior between elderly pedestrians and non-elderly pedestrians. Secondly, the effects of the possible crosswalk configurations on the users' behavior became clear.

Regarding the first aspect, it became clear that elderly users are more cautious (as evidenced by the predominantly positive values of the Kerb Delay and the high frequency of legal crossings), especially in the configurations perceived as hazardous (e.g., a particularly long crosswalk located at a considerable distance from the entrances of the roundabout). On the other hand, non-elderly pedestrians tend to behave more aggressively, as evidenced by a pronounced tendency to anticipate the crossing maneuver (negative values of the Kerb Delay) and a very high percentage of crossings made illegally outside the crosswalk.

On the other hand, when considering the role of pedestrian crossing design elements in influencing pedestrians' behavior, the most significant finding was that relating to the controversial role of refuge islands. The absence of refuge islands seems more likely to encourage users to cross the crosswalk regularly than their presence. Moreover, in the presence of a refuge island, pedestrians are generally induced to anticipate the crossing maneuver (negative values of Kerb Delay). The two conditions described above are likely due to the greater safety pedestrians perceive from the presence of refuge islands. When the refuge islands are not present, pedestrians try to achieve a higher level of safety by using the crosswalks more often and thus crossing the street legally.

Anticipation of the crossing maneuver is also an indicator of the greater safety perceived by pedestrians. Indeed, in the presence of the refuge island, they can control only one vehicle flow at a time, are exposed to a lower risk of accidents due to shorter pedestrian distances, and are consequently induced to anticipate the start of crossing maneuver more frequently.

4. Conclusions

This study investigated pedestrian behavior when crossing the legs of roundabouts with crosswalks that have different geometric configurations. In order to encourage legal pedestrian crossing behavior the results of the present study reasonably suggest implementation of refuge islands at the legs of roundabouts in combination with devices (e.g., chain barriers and bollards) suitable to discourage pedestrians from crossing outside the crosswalks, thus directing them to the mandatory path leading to the zebra crossing protected by the refuge islands.

Finally, it is believed that the research results can help refine the algorithms underlying the operation of automated vehicles that need to interact with road users such as pedestrians who, for obvious reasons, have nothing "automatic" about them and are instead affected by the typical unpredictable aspects of human behavior. Indeed, this study has made it possible to identify the situations in which one of the two possible behaviors of pedestrians initiating the crossing is more likely, i.e., anticipation or delay. It is intended to continue research activities to systematically identify the conditions that determine the greatest likelihood of a anticipated or delayed pedestrian crossing. In particular, the aim is to better define the influence of the following elements: geometric characteristics of crosswalks (e.g., width, length, position in relation to the entrance to the roundabout), street furniture elements (e.g., traffic islands, pedestrian barriers), pedestrian characteristics (e.g., age, gender) and traffic conditions (e.g., traffic volumes, operative speeds). Scientific research will thus be useful in optimizing the software that allows automated vehicles to work out the best actions to take in the event of an interaction with pedestrians. In this way, some of the behaviors of pedestrians that are considered unpredictable could be embedded in behavioral schemes that can be transformed into algorithms useful for improving self-driving vehicles. This will ensure a higher level of safety for pedestrians, who will continue to be the most vulnerable road users even with the proliferation of automated vehicles.

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