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Pedestrian safety at roundabouts: a comparison of the behavior in Italy and Slovenia

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Abstract

Background: Roundabouts are considered one of the safest infrastructure typologies, when referring to motorized traffic. Due to their ability to reduce conflict points between vehicles, they have been largely spread, substituting signalized or unsignalized intersections. While the increase in safety for drivers has been largely tackled and demonstrated by researchers, and some efforts have been spent on the side of cyclists, pedestrian safety has not been extensively analyzed yet. Aim: The present paper aims at analyzing pedestrian safety at roundabouts set in two different locations, Italy and Slovenia. This research will highlight differences and similarities in the behavior of walkers at the same type of infrastructure, taking into account the effects risen by diverse road habits typical of the two countries. Methodology: Starting from video footages recorded at the two locations, behavioral analysis, pointing out pedestrian speed, acceleration and crossing time, and a proactive safety analysis, calculating surrogate safety measures for vulnerable road users, have been run. Descriptive statistics and additional statistical tests are developed to compare the two data samples. Conclusions: From the behavioral point of view, results show for both locations faster pedestrian paces than expected, with the Slovenian case having the highest speed values and lowest crossing times. As regarding the safety point of view, Time-to-Collision, Time Advantage and relative speed between oncoming vehicles and the crossing pedestrians permitted to objectively evaluate conflict severity. The calculated percentages of values overcoming the individuated thresholds for determining dangerous events underlines the need to find solutions from both the infrastructural side and pedestrian awareness about their safe behavior.

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Keywords: pedestrian behavior; pedestrian safety; roundabout.

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1. Introduction

The use of roundabouts is increasing in whole Europe. This kind of road infrastructure is considered by technicians an efficient way of improving road safety level, since they let speeds decrease, avoid direct conflict points among motorized users and permit a more fluent road flow (Persaud et al. (2001), Montella (2007), Lenters (2005)). The study of roundabout's way of functioning from the point of view of motorized users has been focus of many authors (Di Stefano et al. (2018), Macioszek (2017), Zhao et al. (2017)), and various researchers are making a lot of efforts in individuating new and better roundabout configurations (Tollazzi (2015), Giuffrè et al. (2017)), but still little attention has been kept by the point of view of vulnerable road users, specifically, pedestrians.

The aim of this paper is to focus on pedestrian behavior and highlight the impact on roundabout intersection safety by analyzing video footages to investigate near misses and surrogate safety measures, as a mean to achieve proactive safety solutions. In this work, particular behaviors of pedestrians crossing on this kind of infrastructure are investigated in two different locations - Italy and Slovenia - in order to understand if there are different behaviors and how these differences effectively influence pedestrian safety. The advantage of the developed method is the preventive study of human behavior, which allows to analyze the problem before a fatal situation occurs (Laureshyn (2010)). The paper is organized as follows: the first section reviews the current state of-the-art on pedestrian behavior and safety at roundabouts, the second section summarizes the data collection methodology, the third section shows the results obtained by behavioral and safety data, and finally conclusions are drawn.

2. Related works

Recently vulnerable road users' behavior at roundabouts has gained interest and byciclists' behavior has been extensively studied (Poudel and Singleton, 2021). The design, safety and perception of this kind of infrastructure are themes, that have been tackled. Standing to Poudel and Singleton (2021) 49 articles dealt with bicycle safety at roundabouts, of these 32 are crash data studies. Bicyclists' perception of roundabouts was tackled by 8 studies, among which there are Arnold et al (2010), Cambell et al. (2006), Hyden and Várlelyi (2000), Jensen (2013), Møller and Hels (2008), Tan et al. (2019), which investigate their comfort, risk, danger and avoidance of this kind of infrastructure, while design characteristics have been investigated by five research works, among them Brüde and Larsson (2000), Daniels et al. (2010), Hels and Orozova-Bekkevold (2007), Turner et al. (2009). Pedestrian safety at roundabouts has also been identified as an important issue. Nevertheless, little work has addressed it and conflicting results have been obtained. Two studies have emerged in America, one as part of an NCHRP project (Harkey and Carter, 2006) and one for Federal Highway Administration (Carter et al., 2006). The latter (Carter et al., 2006) conducted data collection in Miami, Philadelphia and San Jose, and linked different types of intersections to pedestrian, cyclist and motorist behavior. The authors developed indices for each type of infrastructure surveyed to rank intersections based on pedestrian safety. The former (Harkey and Carter, 2006) developed an observational study of 10 approaches at 7 roundabouts in America. It examined pedestrian risk and found that it increased for pedestrians crossing on roundabout exit legs and on two-lane pedestrian crossings; it also found a range of pedestrian speeds that was similar for all typologies of analyzed crossings, 1.22 m/s to 1.52 m/s. In contrast to (Harkey and Carter, 2006), (Jordan, 1985) and (Tumber, 1997) pointed out that more accidents occur at roundabout entries and that controlling this part of the infrastructure would lead to an improvement in safety at exits as well (Jordan, 1985). As can be seen, the issue of pedestrian safety at roundabouts remains an open one and opposing opinions can be found in the literature. One fact on which most research studies agree is that although roundabouts may be safer than other intersections, they are typically perceived by pedestrians as more dangerous (Lenters, 2005), Stone et al., 2002). Finally, it should be noted that, unlike for vehicular traffic, for which the improvement in safety is clearly stated, for pedestrian safety an improvement is suspected by various authors, but without any certain data being given. According to Stone et al. (2002), converting conventional signalized intersections to modern roundabouts could reduce the number of accidents involving pedestrians and improve safety due to reduced speeds and fewer conflict points. Nevertheless, the authors also mention some additional open issues: the need for pedestrians to properly assess gaps to cross, the longer crossing distances, the usually higher traffic flows, and the constantly moving vehicles. Ultimately, there is no clear and accepted framework for pedestrian behavior and safety at roundabouts, so new research studies may provide additional useful knowledge about this.

3. Methodology

The following subsections introduce the two studied locations, explain the data collection and the elaboration approach.

3.1. Case study locations

Two sites were selected, one in Italy and one in Slovenia (Figure 1). In both cases, a pedestrian crossing at the entry-leg of a two-lane roundabout is studied.

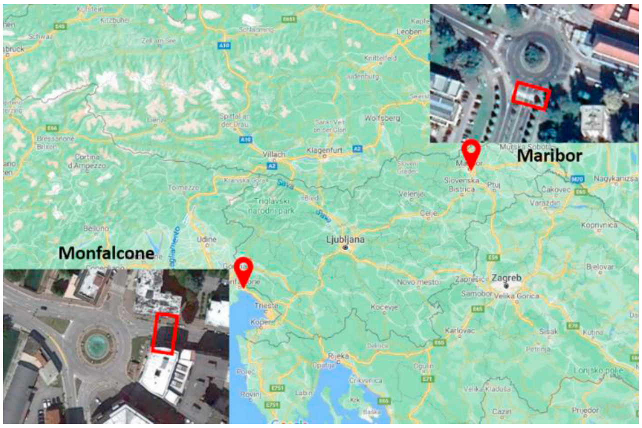

Figure 1. Geographical framework and identification of the two studied crosswalks.

The first location is in the northeastern part of Italy, more specifically in Monfalcone, a medium-sized town of Friuli Venezia Giulia. The roundabout where recordings took place is still part of the urban area of the city, connecting the city centre with all the possible destinations of the nearbies. 3 of the 5 roundabout legs are designed for only one type of manoeuvre, i.e. they are only entry or exit legs, while the remaining two are suitable for both manoeuvres. Pedestrian crossings are present on each of the legs: 4 out of 5 crossings are unsignalized, while the last one is a signalized crossing on the main exit leg. The pedestrian crossing under study crosses two other two unidirectional lanes and is frequented by both vehicular traffic and pedestrians. Indeed, many offices, cafes and other commercial activities are located in its vicinity. The pedestrian flow is mixed: children, adults and elderly were observed, yet adults and young adults represent the majority of recorded people.

The second site under study is located in the northeastern part of Slovenia, more precisely in Maribor. Also, in this case it is a medium-sized city and the chosen roundabout, similarly to the Italian one, belongs to the urban area of the city and distributes traffic from the city center to all possible destinations and vice versa. Also in this case, the roundabout is located near many cafes, houses and offices. An important element of the area is the student campus: from here, many students cross the road on the pedestrian crossing to reach their faculties. This explains the large number of young adults observed, although some adult and older individuals were also observed. The only difference between the two crossings is that at the Italian site, pedestrians finish their crossing action directly on the pavement, while at the Slovenian site they reach a pedestrian refuge island and then cross a single-lane exit leg. Table 1 summarizes the geometric and flow characteristics of the two sites.

Table 1. Geometrical and flow characteristics of the pedestrian crosswalk set in Slovenia.

	Italy	Slovenia		Italy	Slovenia
Crossing length (m)	10.25	12.50	Pedestrian flow (ped/hr)	300	360
Crossing width (m)	4	4	Vehicular flow (veh/hr)	960	1080

3.2. Data collection and elaboration approach

The method used to develop this study consisted of 5 steps that were carried out in parallel at the two sites (Figure 2).

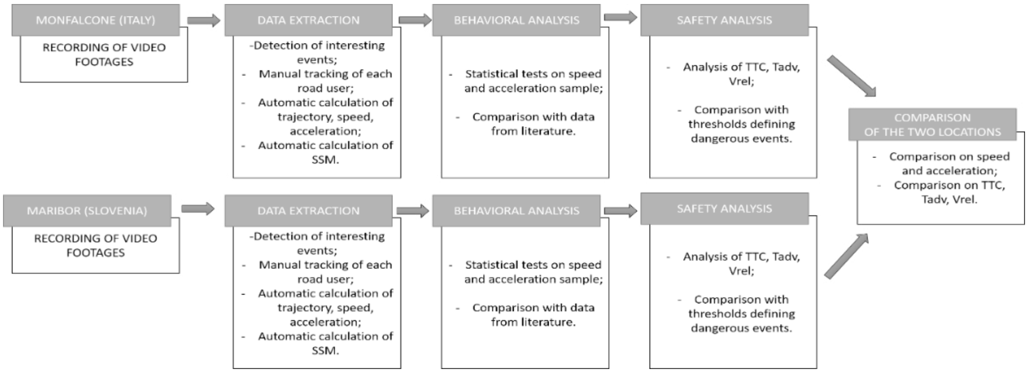

Figure 2. Schematic representation of the data collection and elaboration approach.

First, video recordings were made at the sites in Italy and in Slovenia. They were taken with an action cam mounted on a signal pole to record the entire width of the road, the crosswalk and the entry leg of the roundabout. The footages were recorded during the month of February, on cloudy and dry days, from Monday to Friday, from 8am to 10am. The second step consists of data extraction: this passage was developed thanks to the semi-automatic detection and tracking software T-Analyst, which allows obtaining both behavioral variables, such as speed and acceleration, and surrogate safety measures, such as Time-To-Collision and Time Advantage. The process for obtaining valuable data is to manually identify events of interest, such as near misses, which are automatically stored by T-Analyst in shorter 14-s videos. On these shorter recordings, each road user involved in the event should be manually tracked and their trajectories smoothed. Then, trajectory, speed, and acceleration data are automatically calculated by the software. Finally, for each event of interest, the two involved road users should be labeled so that the software can calculate the surrogate safety measures: Time-To-Collision (TTC), Time Advantage (TAdv), and relative speed (Vrel). At the end of data extraction two databases with a total of 253 observed pedestrians (139 and 114 individuals for the Italian and the Slovenian location respectively) were obtained with the same information typology for both locations, i.e., pedestrian ID, gender, age range, trajectory, average speed, average acceleration, average crossing time, Time-To-Collision, relative speed and Time Advantage. On this data the subsequent analyses were developed: the analysis of the behavioral data was elaborated as third step by developing statistical tests on crossing time, speed and acceleration samples and comparing the results with literature values. The fourth step consisted in investigating the surrogate safety by analyzing the retrieved quantities, TTC, TAdv and Vrel. A comparison has been worked out with the main thresholds found in the literature was elaborated in order to highlight the safety level of this type of infrastructure. At the end, a comparison and contrast of the two sites was carried out to highlight the differences in pedestrian behavior and their impact on safety.

4. Analysis and results

This section presents the two analyses developed and the comparison between the two sites. For better readability, two subsections have been created: the first refers to the behavioral variables, the last to the surrogate safety.

4.1. Behavioral analysis

Behavioral analysis consists of separately elaborating crossing time, velocity, and acceleration data for each location studied. Crossing time is defined as the time (s) it takes a person to complete the crossing, from the moment they leave the sidewalk to the moment they reach the opposite safe side. It was found that Italians have a mean crossing time of 8.27 s, while Slovenians cross the street in 5.94 s on average. It is interesting to note that the Slovenian crossing time is lower for a 2 m longer path compared to the Italian one. This is confirmed by the higher speed of Slovenians compared to Italians, with a mean value of 2.42 m/s and 1.55 m/s, respectively, and by the average higher acceleration of the speed of Slovenians compared to Italians. Table 2 summarizes the descriptive statistics of the three variables for both sites.

Table 2. Comparison of the descriptive statistics for the two locations under study.

	Crossing time (s)		Crossing speed (m/s)		Crossing acceleration (m/s^2)	
	Italy	Slovenia	Italy	Slovenia	Italy	Slovenia
Mean value	8.27	5.94	1.55	2.42	-0.01	0.01
Standard error	0.13	0.09	0.03	0.03	0.02	0.01
Standard deviation	1.54	0.91	0.32	0.35	0.24	0.15
Variance	2.38	0.84	0.10	0.12	0.06	0.02

To determine if the difference on all three variables is statistically significant, a normality test was first conducted for crossing time, speed, and acceleration in order to choose the appropriate further analysis. The Anderson-Darling normality test is based on the assumption that the tested population is normally distributed (null hypothesis) and confirms or rejects this statement depending on the calculated p-value. Figure 3 shows the results of the Anderson-Darling test for all variables considered at both sites and a confidence level of 95.0%. As can be seen from Figure 3, none of the variables can be assumed to follow a normal distribution. Therefore, the nonparametric test Mann-Whitney was performed to determine if the two populations of each behavioral variable are statistically different. This test can be reliably applied to non-normally distributed independent samples. It tests whether the medians of the two populations are different at the chosen confidence level, i.e., 95.0%. From Table 3, it can be seen that for all magnitudes, the difference between the medians of the two samples is different from zero. The confidence interval for this difference indicates whether there is a statistical difference between the two samples. For crossing time and crossing speed, this can be established beyond doubt, as they have a confidence interval not containing zero, whereas it cannot be confirmed for acceleration. This is also to be expected, since the acceleration values in the considered case are very restrained and variable within each sample.

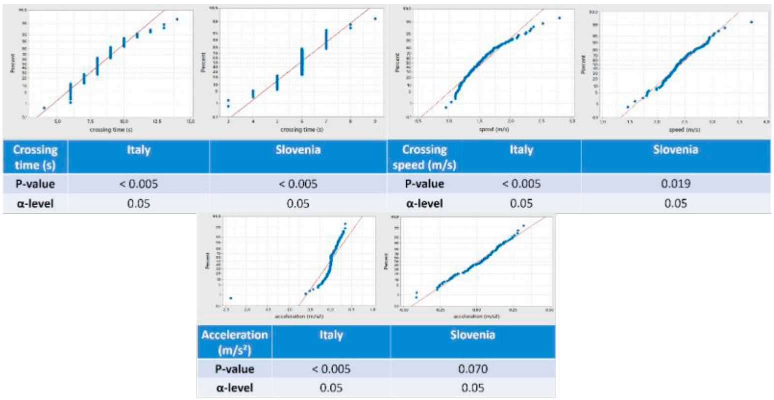

Figure 3. Results of Anderson-Darling normality tests for crossing time, speed and acceleration in Italy and Slovenia.

Table 3. Results of Mann-Whitney's test.

	Italy (η_1)	Slovenia (η_2)	Difference of medians (η_1- η_2)	CI for (η_1- η_2)	p-value
Crossing time (s)	6.00	8.00	-2.00	(-2.00; -1.99)	<0.0005
Crossing speed (m/s)	2.37	1.49	0.89	(0.81; 0.96)	<0.0005
Crossing acceleration (m/s^2)	0.03	0.01	0.01	(-0.03; 0.04)	0.64

Finally, comparing the calculated p-values with the chosen confidence level α=0.05, it can be seen that the statistical difference is confirmed for the two samples of crossing time and crossing speed, while the acceleration populations cannot be treated as statistically different.

4.2. Safety analysis

In addition to the previous behavioral analysis, the safety of pedestrian crossings at roundabouts is evaluated using surrogate safety measures, specifically Time-To-Collision (TTC), Time Advantage (TAdv), and relative speed (Vrel). These measures are well defined in the literature and some thresholds for the same are provided to identify potentially risky situations. According to (Hayward, 1971), TTC is defined as the time needed to cause a collision if the two involved road users continue on their current course at the current speed. Often, the minimum value of TTC is used to evaluate the safety level: Aliaksei et al. in (Laureshyn et al., 2010) gave a safety threshold for TTC_{min} of 1.5 s, with values below this indicating potentially dangerous situations. TAdv, is also defined as a continuous Post-Encroachment Time (PET) and indicates the time interval between the moment the first road user leaves the path and the moment the second road user reaches it (Laureshyn et al., 2010). The threshold value of TAdv for detecting dangerous situations is set to 1 s by (Laureshyn et al., 2010). Based on these definitions, an evaluation of the two pedestrian crossings was conducted. Table 4 summarizes the data on TTC obtained for the two locations. Both the Italian and Slovenian pedestrian crossings appear to have a high safety level, with TTC mean values of 3.11 and 4.52 s, respectively. Nevertheless, it can be noted that Italy has a higher percentage of cases where the TTC was lower than 1.5s - 20.75%, than Slovenia - only 2.41%.

Table 4. Basic statistics about TTC (s), TAdv (s) and Vrel (m/s).

Time-To-Collision TTC	Italy	Slovenia	Time Advantage TAdv (s)	Italy	Slovenia	Relative speed (m/s)	Italy	Slovenia
Mean value	3.11	4.52	Mean value	5.12	7.35	Mean value	7.12	3.39
Standard deviation	1.22	0.49	Standard deviation	9.68	7.04	Standard deviation	4.94	0.54
Minimum	0.97	0.00	Minimum	0.00	1.56	Minimum	1.00	2.62
Maximum	9.94	11.27	Maximum	168.1	30.80	Maximum	25.4	4.43
Percentage < 2.5 s	26.38	9.64	Percentage < 1.0 s	43.61	1.55	Percentage > 10 m/s	58.65	0.00
Percentage < 1.5 s	20.75	2.41	-	-	-	Percentage > 5 m/s	87.22	8.35

Similar to TTC, TAdv was also analyzed based on the defined thresholds (Table 4). Although, also in this case, generally high average values of this measure for both sites indicate an adequate level of safety, 43.61% of the recorded situations in Italy show a value below 1.0 s. In contrast, the Slovenian crossing shows only 1.55% of situations with a TAdv value below 1.0 s. Finally, an essential element when considering pedestrian safety is the speed difference between the motorized vehicle and the pedestrian. Various studies have shown that when the vehicle speed is 48 km/h, 45% of pedestrians are killed, while when the speed is reduced to values of 32 km/h or less, the percentage of pedestrians killed also decreases to 5% (Fortujin, 2003). Interestingly, the mean values of the relative speed between the crossing pedestrian and the arriving vehicle at the studied sites are 7.12 m/s in Italy and 3.39 m/s in Slovenia. Moreover, in Italy, 58.65% of the recorded encounters had a speed higher than 10 m/s, i.e., 36 km/h, and 87.22% had a speed higher than 5 m/s, i.e. 18 km/h (Table 4). The statistical data within this analysis at the two observed roundabouts indicated a higher level of safety at the roundabout in Slovenia. For relevant conclusions, it is necessary to observe and statistically process a much larger database of collected data at a large number of different roundabouts in both environments.

5. Discussion

In previous sections the crossing actions at two different locations, one set in Italy and one in Slovenia, were compared. Both a behavioral analysis and a safety analysis of pedestrians' movements in interaction with traffic were worked out. The goal of this initial research was to obtain the main characteristics of this kind of action at the two locations and to highlight contrasts and similarities. The crossing action can be divided into two main parts: an approaching period, when the pedestrian reacts with his/her specific reaction time to the vehicular presence and judges the available gap time, and the effective crossing action, when the individual leaves the sidewalk to cross the street and reaches the other safe side. This last part and its features are tackled in this research from both a behavioral viewpoint – when the movement characteristics of each single pedestrian are considered, and from a safety point of view – when the interaction with the vehicles effectively occurs. The results of the behavioral analysis at the two observed roundabouts in different urban areas show a large difference in the mean values of crossing time and speed between Italy and Slovenia, the latter being on average 0.87 m/s higher than the former. This difference can be explained by two observations. The first one is related to the distribution of pedestrian flows: although pedestrian flows are mixed at both sites, with younger and older people crossing the road, in Slovenia the vast majority of pedestrians are students, which could influence the higher speed. The different vehicular behavior at the two sites may also be a reason for the faster pace at the Slovenian site: in Slovenia, drivers are used to yield at crossing, and usually the yielding distances are large, which encourages pedestrians to accelerate when crossing. In Italy yielding distances are much shorter and pedestrians usually prefer to stop and wait before crossing the road. This different approach is also reflected in the slight deceleration found in the Italian sample and the acceleration reported for Slovenian pedestrians. Since speed is the most reliable variable to compare pedestrian behavior at different intersections, and few efforts have been made to define the speed pedestrians need to cross roundabouts, a comparison is made between the results found in this study and those found in the literature for unsignalized intersections (Table 5).

Table 5. Comparison of pedestrian crossing speed (m/s) on different types of crosswalks.

Authors of the study	Location of the study	Speed (m/s)
Gruden, Ištoka Otković, Šraml	Roundabout crossing – Italy	1.55
Gruden, Ištoka Otković, Šraml	Roundabout crossing – Slovenia	2.42
Gruden, Ištoka Otković, Šraml (2021)	Signalized crossing	1.61
Lam and Cheung (2000)	Signalized crossing	1.44
Lam and Cheung (2000)	Non signalized crossing	1.26
Knoblauch et al. (1996)	Signalized crossing (youngers)	1.46
Knoblauch et al. (1996)	Signalized crossing (olders)	1.20

As can be seen from Table 5, in both cases the speeds are higher than at signalized and unsignalized intersections. This may lead to the confirmation of the statement of some authors, that pedestrians feel less comfortable crossing roundabouts and therefore try to leave the crossing as soon as possible. Of particular interest is the high value of pedestrian speed at the Slovenian site, which is higher than the value reported by Knoblauch et al., (1996) for young Americans, who seem to walk even slower than pedestrians of Italian mixed flow, and also for Slovenian pedestrians at signalized intersections. From a safety point of view, it is valuable to note the positive results obtained for the Slovenian site in terms of TTC and TAdv, although both pedestrian and vehicle speeds are much higher than at the Italian site. Also, the relative speed between pedestrians and motorized users near the crosswalk is much lower than the relative speed in Italy. This could also be related to the different observed yielding behavior.

6. Conclusion

Comparing the behavior at the at the two observed roundabouts at the two sites, the Italians were found to have higher crossing times and lower crossing speeds compared to the Slovenians, and the latter were found to have an average accelerated gait, while a slightly slower gait characterized the Italian behavior. This different behavior can be explained by the overall different relationship established between oncoming car drivers and crossing pedestrians. The surrogate safety analysis showed that although there are no serious safety issues at either location, the Slovenian intersection has safer conditions, with a lower percentage of TTC and TAdv values below the defined thresholds for risky situations, and with relative speeds between the involved vehicle and pedestrians much lower than at the Italian intersection. The reasons for these differences may be manifold: on the one hand, the different yielding behavior already mentioned certainly has an important influence; on the other hand, the different design of the two roads and pedestrian crossings may affect safety. In fact, although the two locations have similar geometric features, there are some design differences that should be considered. Interestingly, the design of the whole road where the crosswalk is set in Slovenia, and the partition of the elements at the borders of the same make the road environment clear for drivers and the crosswalk very visible. In contrast, visibility at the Italian site is not adequate, due to various obstacles and parked cars at the roadside. Also, it should be highlighted a limitation of the study: in this research work a comparison of only two locations is run. A higher number of intersections could undoubtedly be beneficial for the research and highlight even more, hidden aspects. In further studies authors will also tackled this aspect, as well they aim to compare also other different intersection typologies and the behavior of pedestrians on the same.

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