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Analyzing traffic conflicts and the behavior of motorcyclists at unsignalized three-legged and four-legged intersections in Cartagena, Colombia

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ABSTRACT

Introduction: The global motorcycle market has grown significantly, with over 770 million vehicles estimated to be in use worldwide. Motorcycle-related road traffic deaths in low and middle-income countries (LMICs) like Colombia are concerning, comprising 30% of all reported fatalities. Cartagena has an average of 70 motorcycle-related deaths annually between 2019 and 2022, making it a high-risk area for motorcyclists.
Objective: The study aimed to identify factors associated with motorcyclist safety at unsignalized three-legged and four-legged intersections in Cartagena by observing the behavior of the motorcyclists and the analysis of the potential traffic conflicts. The observational analysis focused on the access of motorcyclists from a secondary road to a main road since it is the behavior offered by the most significant road interaction and the potential risk of traffic conflicts due to crossing.
Methods: The observational process was consolidated at ten three-legged intersections and seven four-legged intersections. Thirty-six hours of videos were collected considering different time slots and weekdays randomly distributed during September 2019 and March 2020. The selection of the intersections included different vehicular flows and road safety conditions. The variables considered in the study were: interaction with other road users, motorcyclist behavior, vehicle handling, potential distractors, and safety elements. The study used the Swedish Traffic Conflict Technique to analyze conflict analysis, incorporating the Post Encroachment Time (PET) measurement. The analysis was developed with descriptive and inferential statistical techniques. The collected variables were analyzed individually (frequency analysis), and contrasts were conducted with the PET values. The study evaluated associations between motorcycles and other motorized road actors at intersections about behaviors and crossroads.
Results: In the Records, 10,281 motorcycle accesses at three and four-Legged Intersections were interactions with other road users, where 2417 and 1903 resulted in potential traffic conflicts, respectively. Average potential conflicts per hour were 115 and 127 at three and four-legged intersections. At the two intersections, the average PET values in motorcycles were between 2.09 and 2.10 s, while in the other motorized road users, it averaged around 2.67 to 2.71 s. In the road conditions, it was identified that intersections with a traffic flow of<10,000 vehicles/day and poor visibility to the left of the intersection lead to more unsafe conditions for motorcyclists. Motorcycle taxi drivers were the user group most frequently involved in traffic conflicts. Actions on the part of motorcyclists, such as risky behaviors, not using helmets, not using turn signals, and not waiting patiently for access, showed a relationship with the potential for traffic conflicts. Finally, turns to the left, particularly the indirect turn to the left on the opposite road, showed a greater risk of traffic conflicts.
Conclusions: The study found that motorcycles exhibit more severe traffic conflicts than motorized vehicles at intersections. Infrastructure conditions significantly impact the risk of intersection conflicts. Individual behaviors such as not stopping at intersections and driving recklessly increased the risk of traffic conflicts. The study recommends improving infrastructure such as visibility and signaling and implementing separators to reduce travel speed and traffic conflicts for motorcycles.

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1. Introduction

Approximately 1.3 million people die in road traffic crashes yearly (WHO 2019). It is estimated that 90% of these deaths occur in low- and middle-income countries (LMIC) (WHO, 2022). In 2019, traffic crashes were the second cause of violent deaths worldwide, with an estimated 16.53 deaths per 100,000 people per year (IHME, 2019). Motorcyclists, cyclists, and pedestrians account for roughly 50% of vulnerable road users who die worldwide. Road traffic crashes are the primary cause of death among children and young people aged 5–29 (WHO 2019). In developed countries where road safety for motorcyclists is less of a concern, initiatives have been implemented to improve the risk conditions these vulnerable road users face. One practical approach involves conducting studies to gather direct information on the roads and generate safe countermeasures (Williams, et al. 2015). Road traffic crashes are a significant challenge for emerging countries, accounting for approximately 5% of their gross national product (WHO, 2022). Road crashes without effective countermeasures could become the fifth leading cause of death in the world by 2030 (Peden, et al. 2019).

The global motorcycle segment is estimated at more than 770 million vehicles. Motorcycles are a means of daily transportation for mobility, sports, and economic activities. Motorcycles have increased because they are compact, agile, economical, and easy to maneuver in congested areas (Ospina-Mateus, et al. 2019). About 30% of all road traffic deaths reported involve powered two-wheelers or motorcycles (mopeds, scooters, and electric bicycles) (WHO 2018). In 2016, Colombia ranked tenth worldwide, third in America, second in South America, and sixth in middle-income countries, with 9.7 fatalities per 100,000 people per year (Ospina-Mateus, et al. 2020). In Colombia, between 2012 and 2022, motorcycle traffic crashes registered an average of more than 3,000 fatalities and 20,000 injured victims annually (ONSV 2022). The road crash rate of motorcyclists corresponds to 52% of fatalities and 53% of injured victims.

Studies of the causality of road crashes in motorcyclists in Colombia are limited (Ospina-Mateus, et al. 2020). The present research developed an observational analysis of motorcyclist behaviors and traffic conflicts to identify potential risks of road traffic crashes. The study was carried out in Cartagena (Colombia), one of the seven most dangerous cities for motorcyclists in Colombia, where approximately more than 75,000 circulate, and around 65% are dedicated to informal transport. The study aimed to identify factors associated with motorcyclist safety at unsignalized three- and four-legged intersections. In the study, the terms “motorcycles” and “powered two-wheelers” are used interchangeably, with a preference for the term “motorcycle” to align with the Latin American context. It is important to note that when referring to these vehicles, the scope also includes mopeds, scooters, motorbikes, and electric or motorized bicycles.

The study utilized the Swedish Traffic Conflict Technique to observe various variables related to road safety, including temporary, operational, and vehicle conditions. The analysis used the post-encroachment time (PET) as a surrogate road safety measure. By analyzing large amounts of information, the study aimed to identify repetitive patterns that explain road behavior, interactions, and traffic conflicts and establish effective countermeasures for road safety.

Motorcycles require balance and stability to ride with at least two points of support. Research on motorcycle road safety is increasing, especially in emerging countries (Ospina-Mateus, et al. 2019). Understanding the factors associated with potential risk events in traffic with vulnerable road users requires identifying significant aspects in the individual, environment, and vehicles and analyzing unsafe road actions. From this perspective, observational techniques are affordable and quick to implement, as Van Haperen, et al. (2019) recommended. Observational behavior studies can be integrated with analyzing traffic conflicts and supported by surrogate safety measures (Polders, et al. 2018).

1.1. Observational analysis of behavior in motorcyclists

Observational methods quickly gather detailed data on road user behavior, capturing frequent risky actions. Participants are generally unaware and act spontaneously, providing unbiased and unsuspecting data, including risky and aggressive behavior. This technique enables analysis of significant factors before a crash, including road actors, vehicles, behaviors, interactions, speeds, and displacements, allowing for comprehensive measurement and anticipation of crashes (Van Haperen, et al. 2019).

Observing motorcyclist behavior helps identify the causes of road crashes. Sensation-seeking and impatience can influence their actions (Wong, et al. 2010). Risky behaviors include speeding, disobeying signals, and not yielding. Observational studies of motorcyclists are a current trend in scientific literature, with only 4.5% of studies involving them (Van Haperen, et al. 2019). Observational techniques involve video cameras and manual records for comprehensive data collection. This method allows for reliable and repeated analysis of recorded behavior. According to Polders, et al. (2018), observation can capture various aspects of behavior, such as interaction style, attitudes, vehicle handling, distractors, safety elements, environmental interpretation, and individual characteristics like gender and age.

Studies using observational techniques on motorcycles include: Zamani-Alavijeh, et al. (2010) found that road infrastructure and other road actors provoke risky actions. Walton, et al. (2012) observed that motorcyclists travel faster and accelerate with better visibility. Zhang, et al. (2014) found that 35% of motorcyclists committed aberrant behaviors at mixed-traffic intersections in China and determined that 35% committed aberrant behaviors such as riding in the opposite lane. Temmerman, et al. (2016) investigated the speed of motorcyclists in Belgium, showing that motorcycle speeds were higher than automobile speeds. Md Isa, et al. (2021) analyzed turn signal behavior in Malaysia and evidenced that the riders initiated the turn signals before crossing the line along highways at intersections.

1.2. Traffic conflict analysis

Traffic conflicts or “near-crashes” are road events with short margins in time and space that could result in crashes or collisions. In these events, at least one of the road users takes an evasive action to avoid the collision (Laureshyn, et al. 2010). The Traffic Conflicts Technique, such as the Swedish Traffic Conflict Technique (S-TCT) developed at Lund University, provides reliable measurements and objective severity ratings of potential collisions quickly and efficiently, using surrogate conflict indicators measures. These indicators include collision time (TTC), Post Encroachment Time (PET), and deceleration-based measures. S-TCT classifies conflicts as severe, slight, and potential (Hydén 1987).

TTC is the possible time to a collision between two road users if their movements remain unchanged. This indicator is one of the most traditional (Mahmud, et al. 2017). PET is calculated as the time between the moment the first road user leaves the path of the second and the moment the second reaches the path of the first. The PET indicator represents the behavior of drivers in the access gap or entrance to an intersection, specifically to potential conflicts with other road users (Hydén 1996). The lower the value of the PET indicator, the riskier and more unsafe the conditions. A PET value of <1 s in urban conditions is considered critical (Paul, et al. 2020).

Studies on motorcyclist traffic conflicts include Nguyen, et al. (2014) analysis of conflicts based on deceleration rate, which found that conflicts were associated with increased traffic flow and sudden braking. Abdul Manan, et al. (2015) examined high-road crashes at rural intersections in Malaysia and concluded that serious conflicts relate to access with a gap of <4 s. Ahmed, et al. (2016) found that motorcyclists involved in conflicts frequently made right turns without braking or signaling. Uzondu, et al. (2019) determined that motorcyclists engage in more unsafe behavior than drivers of other vehicles in Nigeria.

Kronprasert, et al. (2021) found that intersections with low-order controls had a high risk of motorcycle-related conflicts due to the short time to collision.

The traffic conflict technique and observational analysis can be combined to identify better road user behaviors and their impact on road safety. Traffic conflicts are more frequent than road crashes and allow the establishment of surrogate safety measures. The present study combines observational analysis of road behavior and the Traffic Conflict Technique. The research allows a comprehensive road safety diagnosis and risk factors in vulnerable road actors such as motorcyclists. Studies on motorcyclists are still limited and depend on the technical, sociocultural, and spatiotemporal conditions. Based on the findings, recommendations will be proposed to improve road safety for motorcyclists.

2. Material and methods

The study was an observational and cross-sectional analysis of Cartagena (Colombia) motorcyclists. Empirical techniques, such as road behavior observation and the Swedish Traffic Conflicts technique, were employed to collect data. The analysis focused on motorcycle access at unsignalized three-legged and four-legged intersections. The study sought to collect significant aspects of the human factor, environmental conditions and road users involved, and conflicting traffic interaction.

Cartagena is in the northern part of the Caribbean region, and the city has an estimated population of approximately 1.2 million residents and over 130,000 vehicles circulate on its road network. The city covers an area of 650 square kilometers and has a road network of 1,832 lane kilometers. The research focused on Cartagena due to its high rates of road crashes among motorcyclists, with an annual average of 70 motorcyclist deaths occurring between 2019 and 2022 (ONSV 2022). In Cartagena, intersections were identified as the areas with the highest rate of road crashes, accounting for 77% of all crashes, particularly at unsignalized three-legged and four-legged intersections (Ospina-Mateus et al., 2021a; Ospina-Mateus et al., 2021b).

The intersections were selected based on their geometry and similarities in the urban infrastructure. The selection criteria included simple two-way roads with widths ranging from 2.2 to 3.3 m, without separators, a continuous main road without deviations or curves, and a secondary road without priority access. Intersections with high road crash rates and more than five fatal crashes in recent years were considered. The selection of the intersections included different vehicular flows and road safety conditions. Finally, 17 intersections were selected for their feasibility in the physical layout for discreet and careful observation (see Appendix 1). The observational process was consolidated at ten three-legged intersections and seven four-legged intersections. The characteristics of the intersections are described in Table 1.

The observational analysis of traffic behaviors and conflicts focused on motorcyclists entering the intersection from the secondary road onto the primary road. Access to the intersection offers the most significant interaction, particularly crossing conflicts. These conflicts occur in vehicles accessing the main road due to right-turn, left-turn interactions, and direct crossing. Data on other motorized road users were also collected to compare their behaviors and interactions. The information was conducted utilizing a video camera and a pre-designed format. The video recordings were obtained from an unobtrusive location that did not interfere with vehicle mobility and natural flow. The camera was positioned frontally or laterally, 8–10 m from the intersection, as illustrated in Fig. 1. The video collection period included randomly selected time slots and weekdays from September 2019 to March 2020. The study considered 36 h of video recording, with at least two hours per location. The data for this study was collected during Cartagena's summer season, known for its stable and typical weather conditions, including ample lighting and no precipitation.

In the observational analysis, we considered the following aspects: crossing, yielding, driving in the opposite direction, overtaking, location within the road lane, braking, zone of conflicts, evasive actions, waiting time, stopping place, stunts (zigzag, overaccelerate), vehicle handling (lighting, turn signals, occupants, load), distractors (cell phone use, communication), safety elements (helmet, vest, protectors), and interaction with the setting (observation, signs, visibility). We used the Swedish Traffic Conflict Technique to analyze conflict analysis, incorporating the Post Encroachment Time (PET) measurement. PET refers to the gap or time interval between two vehicles entering a conflict point on the road. Specifically, PET is the time it takes for the second vehicle to reach the point of conflict after the first vehicle has cleared the way or completed its passage. A PET value of<1.0 to 1.5 s is considered severe (Hydén 1996). The PET indicator was used as recommended by the literature, given its reliability in measuring traffic conflicts at intersections when supporting photograms about video recordings (Hydén 1996, Mahmud, et al. 2017).

The PET indicator was calculated by analyzing the frames to consider the time elapsed since a vehicle entered the conflict zone and the possible arrival of a second vehicle. The videos were recorded in 4 K format at 60 frames per second to ensure greater precision. The analysis was performed using VLCMP 3.0 software, which allowed for calculating the time between two events. To guarantee the reliability of the information, the extraction process in the videos was prolonged and involved multiple repetitions of frame-by-frame observation, even though the conflicting events were of short duration. This meant that one hour of

Table 1
Description of Selected Intersections.

Label	Location (name address)	Type of intersection (#- Legged)	Type of the main road	Type of secondary road	Annual average of road crashes by motorcyclists (2017–2020)	Traffic volume. vehicles/day	% Motorcycles
1	Dg 32 – Dg 34	3L	collector	local	6	14,168	45%
2	Cra 58 – Cl 31B	3L	collector	collector	5	4,760	64%
3	Cra 83 – Cl 24	3L	collector	local	8	7,348	61%
4	Cl 32 – Dg 33	3L	collector	local	5	6,216	60%
5	Dg 32 – Tv 73	3L	collector	local	4	14,596	54%
6	Cl 32 – Tv 70	3L	collector	local	8	12,320	69%
7	Dg 32 – Tv 69[a]	3L	collector	local	5	8,272	55%
8	Cl 15 – Cra 68[a]	3L	collector	collector	8	9,415	60%
9	Dg 32 – Cr 71b	3L	collector	local	8	11,792	56%
10	Dg 32 – Tv 70	3L	collector	local	8	13,439	56%
11	Dg 32 – Tv 84	4L	collector	collector	6	8,866	45%
12	Cl 30 – Cra 44	4L	collector	local	8	12,342	65%
13	Cl 31B – Cra 56	4L	collector	local	5	6,836	64%
14	Cl 15 – Cra 74	4L	collector	local	10	18,704	61%
15	Cra 30 – Cra 34	4L	collector	collector	7	9,800	60%
16	Cl 30 – Cra 53	4L	collector	collector	9	11,842	65%
17	Cl 30 – Cra 55	4L	collector	local	5	9,784	65%

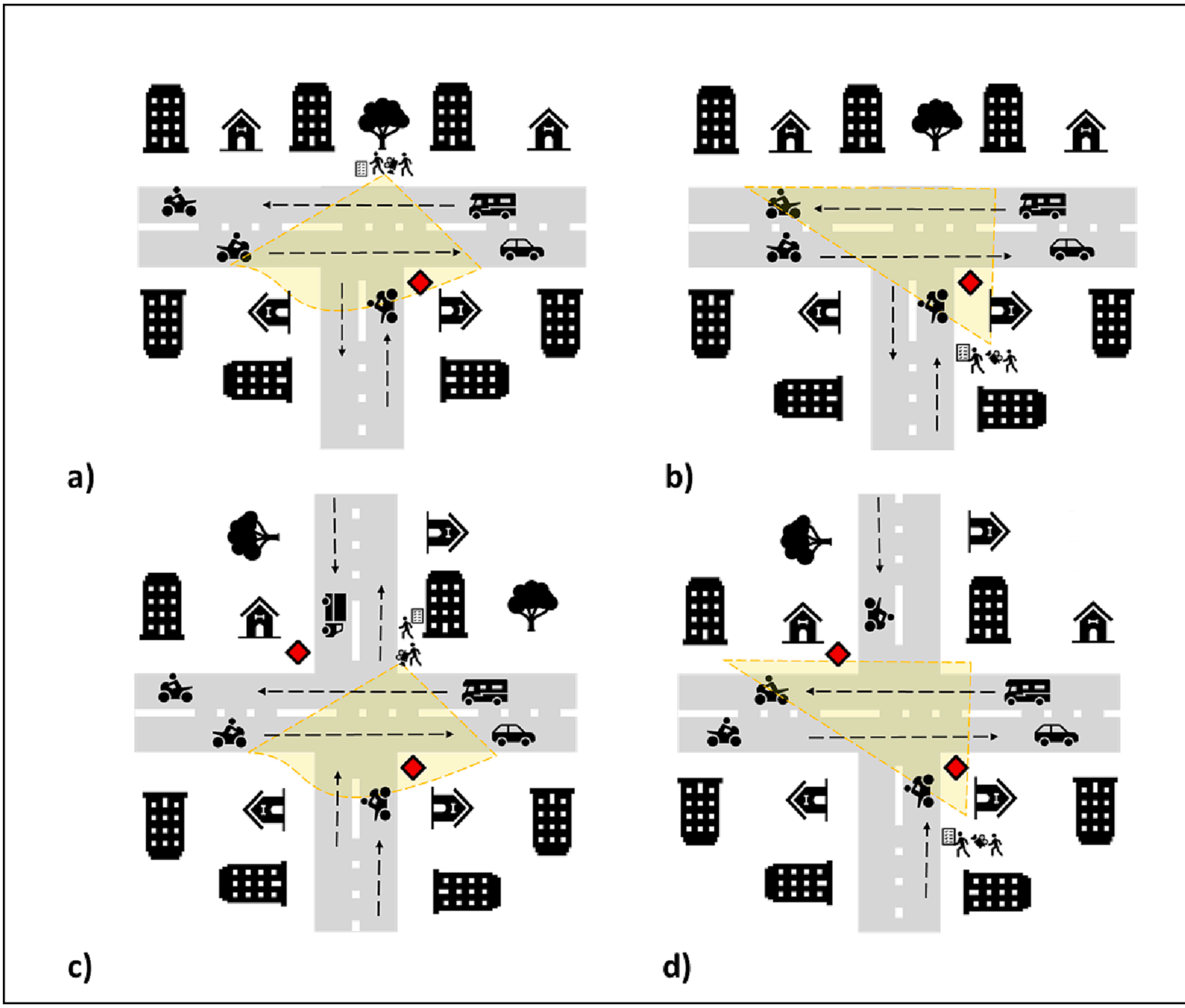


Fig. 1. The perspective of observation of road behaviors and traffic conflicts on the intersections of three Legged (a: frontal; b: lateral) and four Legged (c: frontal; d: lateral).

video processing took about 12 h. The processing was carried out by one of the authors trained with "T-Analyst" software, specifically designed by the University of Lund, for analyzing traffic conflicts using the Swedish technique. Information processing allowed for complementing the recording day data and calculating the surrogate road safety measure with the PET indicator. In the application of the PET Indicator, the trajectory and path of the vehicles were taken into consideration. An essential aspect of replicating the methodology was carefully selecting intersections with similar geometric characteristics. This aspect helped ensure that the resulting conflict assessment was based on comparable and representative data, enhancing the validity and reliability of the analysis.

All the data collected and processed from the video recordings formed a data set. The information was predominantly focused on motorcyclists, but data was also obtained from other motorized road users to compare. Descriptive and inferential statistical techniques, including t-tests and chi-square, were employed in the analysis with a significance level 0.05. The 5% significance level is widely used in statistics and road safety studies for its traditional acceptance and effective balance between detecting effects and minimizing errors. Data were analyzed with Microsoft Excel and SPSS software version 25. Accesses with interactions were considered potential traffic conflicts since collisions are possible (Svensson 1998). In our study, all events classified as conflictive were those with PET values<3.5 s. This approach is consistent with the methodology developed by Paul, et al. (2020) in examining conflicts experienced by motorcyclists at unsignalized urban intersections, where values<1.0 s were considered severe conflicts.

3. Results

3.1. Motorcycles at three-legged intersections

At three-legged intersections, 6,095 motorcycle accesses were registered, with 39.7% resulting in interactions with other road users. During 2,417 interactions, an average of 115 potential conflicts occurred per hour. Off-peak and peak hours showed 83 and 157 potential conflicts per hour, respectively. Mondays (51.2%) and Fridays (71.8%) had the highest proportion of potentially conflictive interactions. The intersections with over 10,000 vehicles/day showed the highest proportion of interactions (45.1%). Motorcyclists riding without passengers had more potential conflicts (61.8%), motorcycle taxi drivers represented the highest frequency of potential conflicts (66.9%), and likewise, the highest ratio for exposure of traffic conflicts at intersections (48%). Youth and young adults were the most frequent motorcyclists (88.8%), and males represented 97% of potential conflicts. Regarding clothing and safety elements, it was found that 70.8% of motorcyclists did not wear reflective vests, 4% did not use helmets properly, 70.7% did not use a helmet visor, 60.3% did not use sun protection for their eyes, 53.3% used sports shoes, 84.9% did not use additional protection, 10.3% drove while talking, and 44.1% held a different helmet on their arm. The characteristics and conditions of the motorcycle with potential conflicts were as follows: 87.8% used a standard motorcycle, 92% had a small engine (90 and 150 cc), 69.2% owned a recent model, 64% had mirrors, and 51.6% did not use daytime running lights.

The study revealed the behavior of motorcyclists when accessing intersections with potential conflicts. Results indicated that 88.6% failed to use turn signal lights, 40.3% did not stop completely, and 40% partially stopped. Of those who stopped, 65.7% did so after the stop line, and 76.9% had a waiting time of<10 s. Moreover, 5.7% of the motorcyclists did not move their heads to observe the road junction. The study found that 46.1% of the crossings were shared or overtaking, 17.1% of the motorcyclists were in the opposite lane before accessing, 44.9% performed previous stunt access, and 14.4% of the turns were to the indirect left in the opposite direction (Indirect left turns in opposite lanes may occur when a motorcyclist crosses the main road without squaring off the turn, resulting in a diagonal entry into the opposite lane.). Finally, it was identified that most of the interactions were with other motorcycles (59.1%), and 35.4% presented evasive actions. The PET value had an average of 2.10 s (S.D. 0.91). Potential traffic conflicts for areas close to intersections are summarized by frequency and PET in Fig. 2. The distribution of the interactions showed that the zones with the most significant potential conflicts were areas close to the access at the intersection (zones “C”, “D”, and “E”) with a frequency between 647 and 515. In the PET measurement, the zone with the most critical PET was found in the center of the intersection (zone “G”), with average values of 1.68 s.

Table 2 shows the results and contrasts between the different variables and the PET value. In total, 257 severe conflicts (PET < 1 Sec) occurred, corresponding to 11% of potential conflicts, and represented an average of 12 severe events per hour. On average, there were 9 and 17 conflicts in off-peak and peak hours, respectively. The area with the highest frequency of serious events was “E”, with 86 conflicts (see Fig. 2. c).

PET during the peak period was lower than off-peak ($p < 0.05$). The PET value was lower at intersections with moderate vehicular flow ($p < 0.05$). Visibility to the left showed a significant statistical difference, with the PET value lower when visibility was poor or obscured ($p < 0.05$). Motorcycle taxi drivers had the lowest PET ($p < 0.05$). Motorcyclists with sun protection for their eyes had lower PET values ($p < 0.05$). Motorcyclists who did not use helmets, mirrors and daytime running lights had lower PET values ($p < 0.05$). Motorcyclists who did not use turn indicators have riskier PET values ($p < 0.05$). Motorcyclists who did not stop before entering the intersection had lower PET values ($p < 0.05$). Motorcyclists who waited more than 10 s to enter had better PET values ($p < 0.05$). Motorcyclists with aggressive behavior obtained lower PET values ($p < 0.05$). Finally, the left turn (normal/opposite lane) obtained lower PET values, in contrast to the right turn ($p < 0.05$).

3.2. Comparisons between motorcycles and other vehicles (Cars, Buses, and Trucks) at three-legged intersections

The following is a comparative analysis between motorcyclists and other motorized road users (including cars, buses, and trucks). The data of other vehicles were collected at the same intersections, with 2,614 entries, out of which 1,123 were identified as potential traffic conflicts. In the other vehicles, the PET value was 2.67 s (S.D. 1.06), and 44 serious conflicts occurred, corresponding to 4% of potential conflicts, and represented an average of 3 serious events per hour. Table 3

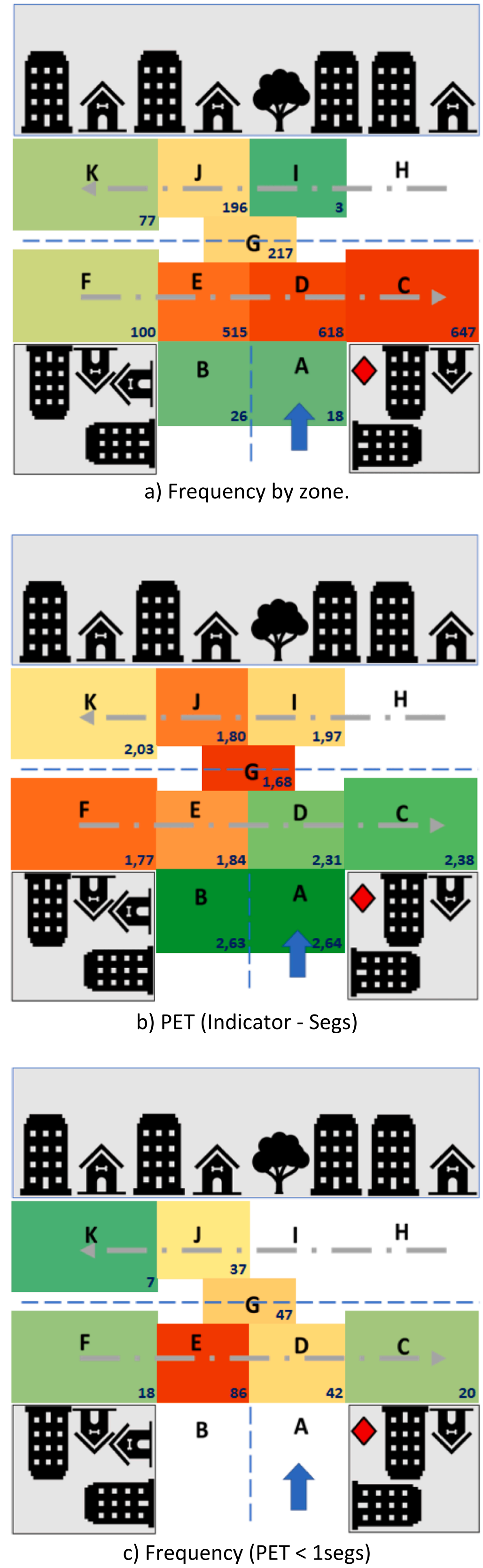


Fig. 2. Performance of traffic conflicts in motorcycles in the different zones defined at three-legged Intersections by (a) frequency and indicator, (b) PET, and (c) Frequency with PET < 1 s.

Table 2
The tabulation of interactions and severe traffic conflict in the attributes and observed behaviors at three-Legged Intersections.

Category		Potential conflicts N	%	Ratio[a] %	PET<1 S N	%	PET Average	S.D.	P-value [b]
Time of Day	Off-peak	1,000	41	37	108	42	2.18	0.97	**0.00***
	Peak	1,417	59	42	149	58	2.05	0.86	
Daily Traffic Flow (vehicles/day)	<10,000 (moderate)	1,276	53	46	152	59	1.99	0.84	**0.00***
	More than 10,000 (high)	1,141	47	36	105	41	2.23	0.98	
Right Visibility	Poor or obscured	1,112	46	34	123	48	2.12	0.93	0.49
	Clear	1,305	54	43	134	52	2.09	0.90	
Left Visibility	Poor or obscured	1,414	59	43	145	56	2.07	0.87	**0.04***
	Clear	1,003	41	35	112	44	2.15	0.96	
Motorcyclist Taxi Rider	Yes	1,616	67	48	192	75	2.05	0.90	**0.00***
	No	801	33	23	65	25	2.21	0.93	
Number of Occupants	One	1,493	62	40	163	63	2.11	0.93	0.78
	Two or more	924	38	36	94	37	2.10	0.88	
Gender	Male	2,351	97	40	252	98	2.10	0.91	0.24
	Female	54	2	43	5	2	2.25	0.86	
Helmet Use -Rider	Yes	2325	96	40	243	95	2.11	0.92	**0.00***
	No	92	4	40	14	5	1.87	0.79	
Motorcycle Vest	Yes	696	29	40	67	26	2.15	0.91	0.12
	No	1,711	71	39	189	74	2.09	0.91	
Sun Protection (glasses or polarized bezel)	Yes	690	29	46	76	30	2.07	0.88	**0.04***
	No	1,458	60	38	140	54	2.15	0.93	
Use of Mirrors	Yes	1,547	64	41	154	60	2.15	0.93	**0.00***
	No	863	36	38	101	39	2.03	0.87	
Use of Daytime Running Lights	Yes	1,136	47	39	116	45	2.15	0.94	**0.01***
	No	1,248	52	40	139	54	2.06	0.88	
Use of Turn Signals	Yes	221	9	35	21	8	2.21	0.92	**0.01***
	No	2,141	89	40	231	90	2.05	0.87	
Access Waiting Time	<10 s	1,111	46	38	77	30	2.29	0.92	**0.00***
	More than 10 Seconds	333	14	38	17	7	2.47	0.96	
Stunts	Yes	1,085	45	41	109	42	2.07	0.85	0.13
	No	1,332	55	39	148	58	2.13	0.96	
Head Movement Prior to Entering	Yes	1,147	47	29	116	45	2.12	0.92	0.76
	No	1,270	53	43	141	55	2.10	0.90	
Turn or access at the intersection	Left	1,278	53	52	212	82	1.84	0.82	**0.00***
	Right	1,139	47	34	45	18	2.40	0.91	
Stop	Yes	1,444	60	39	94	37	2.33	0.93	**0.00***
	No	973	40	42	163	63	1.77	0.77	
Aggressive Behaviors	Yes	1,664	69	44	247	96	1.80	0.74	**0.00***
	No	753	31	38	10	4	2.78	0.90	
Interaction Vehicle	Motorcycle	1,428	59	–	144	56	2.12	0.91	0.54
	Other	989	41	–	113	44	2.09	0.91	
Evasive Action	Yes	851	35	–	80	31	2.05	0.83	**0.03***
	No	1,566	65	–	177	69	2.13	0.96	

a. Ratio. (Contrast of total vehicle accesses vs. entries with potential conflicts).
T-test for comparison between categories. * Statistically significant difference according to *t*-test ($p < 0.05$).

Table 3
Vehicle braking behavior prior to access at three-legged Intersections.

Turning maneuver	Stop	1. Without interactions MC N	%	OV N	%	P-value [a]	2. Potential conflicts MC N	%	OV N	%	P-value [a]	1 vs 2 P-value [b] MC	P-value [b] OV
Right	Yes	1,503	68	871	89	**0.00***	706	62	509	88	**0.00***	**0.00***	0.59
	No	716	32	113	11		433	38	72	12			
Left	Yes	714	58	422	90	**0.00***	540	58	461	89	**0.00***	0.93	0.74
	No	513	42	47	10		391	42	55	11			
Indirect left turn in the opposite direction	Yes	139	60	36	97	**0.00***	198	57	24	92	**0.00***	0.50	0.36
	No	93	40	1	3		149	43	2	8			

MC: Motorcycles; OV: Other Vehicles (Cars, Buses, and Trucks). a. Chi-square test in comparison between types of vehicles. b. Chi-square test that compares vehicle access without and with interaction based on similar vehicles. * Statistically significant difference according to the Chi-sq test ($p < 0.05$)

provides a comprehensive comparison of the behavior of vehicles at intersections, with a particular focus on stopping prior to entry, entrance interactions, and potential traffic conflicts during turning maneuvers. The results of the study reveal that, regardless of turning maneuvers and intersection interactions, it was more common for motorcyclists not to stop prior to entry than other vehicles ($p < 0.05$). In motorcycles that turned right, the frequency with which braking was respected decreased when interactions occurred at the intersection access ($p < 0.05$).

A comparison of PET values was conducted to analyze the access of intersections based on the vehicular flow of the main road. The motorcyclists had significantly riskier PET values than other vehicles ($p < 0.05$). The motorcyclist had more severe traffic conflicts than other vehicles ($p < 0.05$). As presented in Table 4, the findings indicate that motorcycles demonstrated lower PET values ($p < 0.05$) than other vehicles during right and left turns. Moreover, motorcycles exhibited the most unsafe PET value during right and left turns when traffic flow at the intersection was moderate ($p < 0.05$).

Table 4
The contrast of PET value according to the vehicular flow of the main road at three-legged Intersections.

Turning maneuver	Vehicles	General				1. Traffic Flow (<10 K vehicles/day) - Moderate				2. Traffic Flow (More than 10 K vehicles/day) - High				1 vs 2
		N	Average	S.D.	P-value a	N	Average	S.D.	P-value a	N	Average	S.D.	P-value a	P-value b
Right	MC	1,139	2.40	0.91	**0.00***	679	2.22	0.80	**0.00***	460	2.67	1.00	**0.00***	**0.00***
	OV	581	3.07	1.01		305	3.25	1.00		276	2.88	0.99		**0.00***
Left	MC	931	1.85	0.85	**0.00***	503	1.73	0.81	**0.00***	428	1.99	0.87	**0.00***	**0.00***
	OV	516	2.26	0.94		221	2.33	1.00		295	2.21	0.89		0.15
Indirect left turn in the opposite direction	MC	347	1.81	0.76	0.84	94	1.72	0.72	0.20	253	1.84	0.77	0.87	0.15
	OV	26	1.83	0.68		12	1.89	0.39		14	1.86	0.93		0.90

MC: Motorcycles; OV: Other Vehicles (Cars, Buses, and Trucks). a. *t*-test for comparison between types of vehicles. b. the *t*-test in comparison between moderate vehicular flow and high vehicular flow. * Statistically significant difference according to *t*-test ($p < 0.05$)

3.3. Motorcycles at four-legged intersections

At four-legged intersections, 4,186 motorcycle accesses were obtained, with 45.5% corresponding to interactions with other road users. In the 1,903 motorcyclist interactions, an average of 127 potential conflicts per hour were identified. Off-peak and peak hours showed 109 and 139 potential conflicts per hour, respectively. Mondays (46.9%) and Fridays (46.7%) had the highest proportion of potentially conflictive interactions. The intersections with over 10,000 vehicles/day showed the highest proportion of interactions (52.6%). Motorcyclists riding with occupants presented the highest frequency of potential conflicts (50%), %), and motorcycle taxi drivers represented the highest frequency of potential conflicts (53.8%) and likewise the highest ratio for exposure to traffic conflicts at intersections (46%). Youth and young adults were the most frequent motorcyclists (85.2%), and males represented 97% of potential conflicts. The study revealed that most motorcyclists had poor safety habits regarding clothing and safety elements. Specifically, 71% of them did not wear reflective vests, 7% did not use helmets properly, 65.7% did not use a helmet visor, 62.5% did not use eye protection from the sun, 60.5% wore sports shoes, 70.4% did not use any additional protection, 15.7% drove distracted while talking, and 55.5% carried an additional helmet on their arm. The characteristics and conditions of the motorcycles with potential conflicts were as follows: 80.1% of the motorcycles were standard models, 93.5% had small engines (between 90 and 150 cc), 65.1% rode recent models, 71.4% had mirrors, and 68.4% did not have daytime running lights.

According to the study, motorcyclists exhibited various behaviors when approaching intersections with potential conflicts. Among the findings, it was revealed that 87.4% failed to use turn signal lights, 18.4% did not come to a complete stop, and 44.3% only partially stopped. For those who stopped, 76.2% did so after the stop line, and 85.4% had a waiting time of<10 s. Additionally, 9.3% of the motorcyclists did not look around to observe the road junction. The study also reported that 60.1% of the crossings were shared or overtaking, 14.7% of the motorcyclists were in the opposite lane before accessing, 62.7% performed stunts, and 13.2% of the turns were to the indirect left in the opposite direction. The study's analysis revealed that most potential conflicts involved interactions with other motorcycles (68.4%), and 56.1% of those interactions resulted in evasive actions. The PET interval had a mean of 2.09 s (SD 0.84). Fig. 3 summarizes potential traffic conflicts for areas near intersections by frequency, PET value and frequency of severe traffic conflicts. The data indicated that the zones with the most significant potential conflicts were the areas near the intersection access points (zones "C", "D", and "E"), with a frequency between 387 and 497. The PET measurement also identified that zone "I" have the most critical PET, with an average value of 1.54 s.

The PET value and the different variables are compared, and their results and contrasts are presented in Table 5. A total of 128 severe conflicts (PET < 1 Sec), which accounted for 7% of potential conflicts, were recorded, resulting in an average of 9 severe events per hour. The average number of conflicts during off-peak and peak hours was 8 and 9, respectively. Finally, the zones with the highest traffic conflicts found areas "D", "E", and "I," with more than 27 events (see Fig. 3. c).

The PET value was found to be significantly lower at intersections with moderate vehicular flow ($p < 0.05$) and when visibility to the left was poor or obscured ($p < 0.05$). Furthermore, motorcycle taxi riders demonstrated the lowest PET value ($p < 0.05$), while the size of the motorcycle engine had a significant impact on the PET value ($p < 0.05$). Notably, the use of safety equipment, such as helmets, turn signals, and mirrors, was found to be associated with lower PET values ($p < 0.05$), while aggressive riding behavior and waiting<10 s before entering the intersection were linked to lower PET values ($p < 0.05$). Additionally, left turns in the opposite direction exhibited lower PET values compared to other types of entry (right, normal left, direct) ($p < 0.05$).

3.4. Comparisons between motorcycles and other vehicles (Cars, Buses, and Trucks) at four-legged intersections

At intersections with four-legged, we collected data on other motorized road users, such as cars, buses, and trucks, resulting in 1,739 entries. Of these, 47.7% were identified as potential traffic conflicts. In the other vehicles, the PET value was 2.71 s (S.D. 1.14), and 53 serious conflicts occurred, corresponding to 6% of potential conflicts, and represented an average of 4 serious events per hour. Table 6 provides a detailed comparison of vehicle behavior at intersections, focusing on stopping before access, entrance interactions, and potential traffic conflicts during crossing maneuvers. In contrast to other vehicles, motorcycles frequently do not stop at the intersection when no vehicles are on the main road ($p < 0.05$). In contrast to other vehicles, left- and right-turning motorcycles often did not stop when there were interactions ($p < 0.05$).

A comparison was made between PET values to assess the accessibility of intersections based on the flow of vehicles on the main road. Motorcycles had significantly lower PET values ($p < 0.05$). In the frequency of severe conflict events, no significant difference was found between motorcycles and other vehicles (p greater than 0.05). According to the results presented in Table 7, in the moderate and high vehicular flow, motorcycles had more unsafe values in the PET than in the other vehicles and right turns, normal left and direct crossing ($p < 0.05$). The direct crossings of motorcycles had significant differences in PET values when contrasting the vehicular flows at the intersections ($p < 0.05$).

4. Discussion

Our study found that moderate vehicular flow at intersections with motorcycles was significantly associated with potential traffic conflicts. Higher traffic flow at intersections was also observed to be linked with more frequent traffic conflicts. However, intersections with moderate traffic flow posed a greater risk of conflicts. Motorcyclists showed higher levels of risk when crossing intersections with moderate traffic flow, as indicated by the PET indicator. Lower traffic volume at intersections

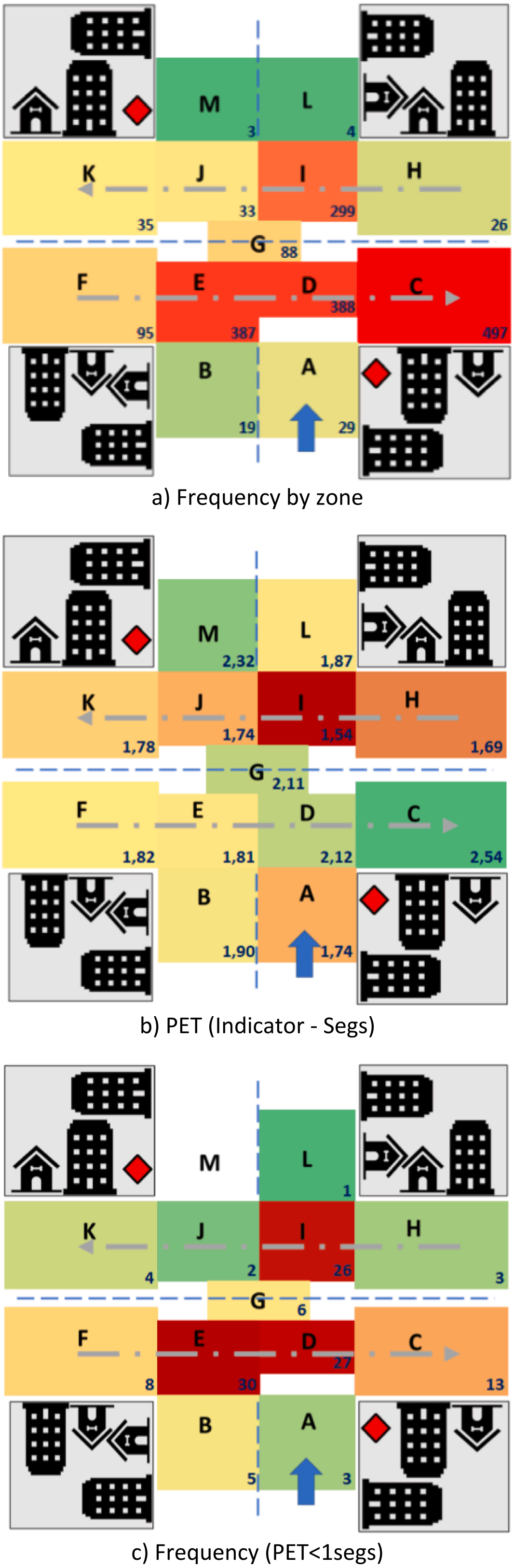


Fig. 3. Performance of traffic conflicts in motorcycles in the different zones defined at four-legged Intersections by (a) frequency and indicator, (b) PET, and (c) Frequency with PET < 1 s.

may induce riders to accelerate, which could be due to the perception of less congestion and the open road. Therefore, riders at intersections with high traffic flow may exhibit greater caution in response to heightened risk and exposure, previously documented in driver behavior and speed regulation studies (Mahona, et al. 2019). Studies at intersections have shown a high relationship between low traffic volume and road crashes (Retallack, et al. 2020).

In the study, road actors highly involved in road conflicts, such as motorcycle taxi riders, were found to have more unsafe PET values than other motorcyclists. The behaviors and risks motorcycle taxi drivers take regarding road safety are distinct from those of regular motorcyclists (Wu, et al. 2016). Motorcycle taxi riders rely on the number of passengers they transport, which means more money, which may create pressure to drive faster and take more risks to maximize their profits. Additionally, they may improvise their route in search of clients or streamline their route to increase their income. Furthermore, motorcycle taxi riders often operate in congested urban areas, where they must navigate through heavy traffic, weave between cars, and make sudden stops and turns to get their passengers to their destinations as quickly as possible. These driving behaviors can increase the risk of road crashes, particularly when combined with other factors such as poor road conditions, weather, or driver fatigue (Ospina-Mateus et al., 2021a; Ospina-Mateus et al., 2021b).

Using certified helmets for motorcycle drivers and passengers in Colombia is mandatory, and non-compliance can result in fines and legal penalties. It is worth noting that in Colombia, there is a tradition of penalizing drivers more severely than passengers for non-compliance with this regulation. In this study, the use of helmets by motorcyclists was frequent in both types of intersections (greater than 90%). In Cartagena, motorcycle taxi drivers are required to wear helmets due to passengers' reluctance to use them. This measure helps drivers evade scrutiny from authorities and regulatory bodies. However, enforcing helmet usage among passengers is challenging due to their tendency to declare themselves undocumented to evade traffic violations.

Consequently, the lack of effective mechanisms to target passengers hampers enforcement efforts. Local statistics indicate a meager compliance rate of around 8% among passengers regarding helmet usage, underscoring the need for improved measures. Studies have shown that motorcycle drivers who do not wear helmets tend to engage in more risky behaviors while riding, consistent with our findings that motorcycle drivers who did not wear helmets had a higher risk of a road crash (lower PET value). Reasons for this behavior could be linked to the belief that helmets are only necessary for extended trips or high-speed activities, and cyclists may refuse to wear them during short trips or quick errands (Grimm, et al. 2016).

In the two types of intersections, a low frequency of turn signal use was observed (approximately 88%). Motorcyclists who did not use turn signals had a higher risk of road crashes due to more risky PET values. Some riders may justify not using turn signals by claiming they are driving too fast, lack time to plan, or the motorcycle's control system is too complex. Others may disregard traffic laws or perceive turn signals as unnecessary. Studies have demonstrated that turn signals can significantly decrease the risk of intersection-related crashes (Rusli, et al. 2020).

On average, 18% and 40% of motorcyclists did not stop before accessing the intersection. This behavior is associated with more unsafe PET values. Motorcyclists may have a reluctance to stop at intersections due to several reasons. Firstly, motorcyclists may avoid stopping at intersections because they risk losing their priority or right of way. Additionally, novice riders may find it challenging to maintain balance when stopping and starting. Additionally, motorcycles have less protection than other vehicles, which may increase their aversion to risk and encourage them to keep moving rather than stop and be exposed to a potential road crash. The behavior of not stopping or braking after the corner exposes motorcyclists to lane encroachment related to potential conflicts, as noted by Das et al. (2022).

Table 5
The tabulation of interactions and severe traffic conflict in the attributes and observed behaviors at four-Legged Intersections.

Category		Potential conflicts		Ratio[b]	PET<1 S		PET		P-value [b]
		N	%	%	N	%	Average	S.D.	
Time of Day	Off-peak	653	34	46	45	35	2.11	0.86	0.34
	Peak	1,250	66	45	83	65	2.07	0.83	
Daily Traffic Flow (vehicles/day)	<10,000 (moderate)	902	47	52	60	47	2.05	0.80	**0.03***
	More than 10,000 (high)	1,001	53	43	68	53	2.13	0.87	
Right Visibility	Poor or obscured	1,370	72	46	97	76	2.10	0.86	0.23
	Clear	533	28	44	31	24	2.05	0.78	
Left Visibility	Poor or obscured	883	46	47	59	46	2.05	0.79	**0.03***
	Clear	1,020	54	44	69	54	2.12	0.88	
Motorcyclist Taxi Rider	Yes	1,023	54	46	79	62	2.02	0.82	**0.01***
	No	880	46	32	49	38	2.16	0.86	
Number of Occupants	One	873	46	45	54	42	2.09	0.83	0.72
	Two or more	1,030	54	45	74	58	2.08	0.85	
Gender	Male	1,845	97	45	123	96	2.08	0.83	0.61
	Female	33	2	42	3	2	2.18	1.02	
Helmet Use -Rider	Yes	1770	93	47	124	97	2.17	0.85	**0.03***
	No	133	7	44	4	3	2.02	0.78	
Motorcycle Vest	Yes	552	29	46	37	29	2.12	0.87	0.38
	No	1,351	71	42	91	71	2.07	0.83	
Sun Protection (glasses or polarized bezel)	Yes	308	16	47	17	13	2.11	0.81	0.62
	No	1,189	62	45	80	63	2.08	0.84	
Engine Size	90–150 CC	1,780	94	45	117	91	2.10	0.85	**0.04***
	150 CC or More	79	4	48	8	6	1.92	0.74	
Use of Mirrors	Yes	1,358	71	46	92	72	2.08	0.83	0.44
	No	387	20	43	24	19	2.12	0.88	
Use of Daytime Running Lights	Yes	482	25	50	36	28	2.13	0.87	0.27
	No	1,302	68	44	84	66	2.08	0.84	
Use of Turn Signals	Yes	128	7	55	4	3	2.25	0.84	**0.03***
	No	1,664	87	44	112	88	2.08	0.85	
Access Waiting Time	<10 s	220	12	50	11	9	2.37	0.86	**0.00***
	More than 10 Seconds	1,333	70	42	74	58	2.14	0.84	
Stunts	Yes	1,193	63	43	84	66	2.09	0.84	0.73
	No	710	37	49	44	34	2.08	0.84	
Head Movement Prior to Entering	Yes	1,380	73	48	94	73	2.08	0.84	0.83
	No	523	27	44	34	27	2.09	0.85	
Stop	Yes	350	18	41	43	34	1.69	0.67	**0.02***
	No	1,553	82	45	85	66	2.17	0.85	
Aggressive Behaviors	Yes	1,506	79	44	126	98	1.90	0.72	**0.00***
	No	396	21	37	2	2	2.79	0.91	
Interaction Vehicle	Motorcycle	1,302	68	–	87	68	2.08	0.84	0.77
	Other	601	32	–	41	32	2.10	0.85	
	No	1,410	74	–	96	75	2.09	0.84	
Evasive Action	Yes	1,067	56	–	73	57	2.07	0.81	0.64
	No	836	44	–	55	43	2.10	0.88	

a. Ratio. (Contrast of total vehicle accesses vs. entries with potential conflicts).
T-test for comparison between categories. * Statistically significant difference according to *t*-test ($p < 0.05$).

Table 6
Vehicle braking behavior prior to access at four-legged Intersections.

Turning maneuver	Stop	1. without interactions MC N	%	OV N	%	P-value [a]	2. Potential conflicts MC N	%	OV N	%	P-value [a]	1 vs 2 P-value [b] MC	P-value [b] OV
Right	Yes	698	85	391	95	**0.00***	555	84	298	92	**0.00***	0.55	0.06
	No	126	15	19	5		109	16	26	8			
Left	Yes	329	79	307	95	**0.00***	297	77	274	93	**0.00***	0.59	0.42
	No	90	21	17	5		89	23	20	7			
Indirect left turn in the opposite direction	Yes	255	77	46	96	**0.00***	204	81	58	88	0.21	0.22	0.14
	No	76	23	2	4		47	19	8	12			
Direct crossing	Yes	585	83	123	97	**0.00***	497	83	130	89	0.06	0.98	**0.01***
	No	124	17	4	3		105	17	16	11			

MC: Motorcycles; OV: Other Vehicles (Cars, Buses, and Trucks). a. Chi-square test in comparison between types of vehicles. b. Chi-square test that compares vehicle access without and with interaction based on similar vehicles. * Statistically significant difference according to the Chi-sq test ($p < 0.05$)

Based on the findings of this study, it was observed that 14% and 23% of motorcyclists tend to experience wait times of more than 10 s while accessing the intersection of three-legged and four-legged, respectively. Studies by Huan, et al. (2014) show that motorists do not want to wait too long to cross intersections. It was found that motorcyclists prefer to enter intersections with the help of another vehicle, as this provides them with a sense of safety. When a motorcyclist shares access with another vehicle, the other vehicle may create spaces and gaps in traffic that allow for easier entry into the intersection. Moreover, sharing access with another vehicle makes the visibility issues that motorcyclists often face difficult. However, positioning oneself near another vehicle can increase the risk of crashes as motorcyclists may become obscured by the larger vehicle and be less visible to other road users. This maneuver requires quick access and can result in loss of

Table 7
The contrast of PET value according to the vehicular flow of the main road at four-legged intersections.

Turning maneuver	Vehicles	General				1. Traffic Flow (<10 K vehicles/day) - Moderate				2. Traffic Flow (More than 10 K vehicles/day) - High				1 vs 2
		N	Average	S.D.	P-value a	N	Average	S.D.	P-value a	N	Average	S.D.	P-value a	P-value b
Right	MC	664	2.54	0.89	**0.00***	218	2.53	0.89	**0.00***	446	2.54	0.90	**0.00***	0.94
	OV	324	3.32	1.05		117	3.39	1.11		207	3.28	1.02		0.37
Left	MC	386	1.89	0.67	**0.00***	224	1.83	0.69	**0.00***	162	1.92	0.64	**0.00***	0.19
	OV	294	2.38	1.03		141	2.47	1.05		153	2.30	1.01		0.16
Indirect left turn in the opposite direction	MC	251	1.74	0.64	0.07	120	1.76	0.64	0.51	131	1.72	0.64	0.06	0.63
	OV	66	1.96	0.88		19	1.89	0.90		47	1.99	0.88		0.68
Direct crossing	MC	602	1.86	0.74	**0.00***	340	1.79	0.74	**0.00***	262	1.91	0.73	**0.00***	**0.05***
	OV	146	2.35	1.00		39	2.33	1.01		107	2.35	1.00		0.89

MC: Motorcycles; OV: Other Vehicles (Cars, Buses, and Trucks). a. *t*-test for comparison between types of vehicles. b. the *t*-test in comparison between moderate vehicular flow and high vehicular flow. * Statistically significant difference according to *t*-test ($p < 0.05$)

visibility when the vehicle in front makes it difficult. Overtaking maneuvers are hazardous and can result in serious injuries (Huertas-Leyva, et al. 2021).

Motorcyclists had more frequent potentially conflicting interactions with vehicles traveling in the lane adjacent to the intersection due to their proximity during the maneuver. In three-legged intersections, the central zone of the intersection had the worse PET value, as it is the area with the greatest concentration of routes and crossings (Vedagiri, et al. 2015). The most frequent sector for severe traffic conflicts in both intersections was the diagonal area to the intersection access (zone E). This area may be related to indirect left turns in the opposite lane, where the motorcyclist crosses the main road lane without squaring off the turn and entering diagonally.

Left turns were the riskiest for motorcyclists, as they must navigate through vehicles in adjacent and distant lanes, resulting in shorter interaction times reflected by the PET indicator. On the other hand, right turns made by motorcyclists were much more predictable for other road users (Muttart, et al. 2017). Motorcyclists commonly made right turns to the right of their travel lane, facilitating the planning of evasive maneuvers and improving the time taken to reach the same conflict point. The PET indicator supported this finding, which revealed better values in these situations.

When analyzing the turning maneuvers performed by motorcyclists at two types of intersections with the visibility offered by the access from the left and right perspectives, additional findings can be established in line with what was previously identified (see Appendix 2-5). The findings show that at three-legged intersections, left turns made by squaring off (almost 90°) cause conflicts in the center of the intersection. Indirect left turns in the opposite direction are one of the maneuvers where visibility difficulties on the left corner make motorcyclists more prone to collision. For this type of entrance, the level of risk for traffic conflicts is similar in both the nearby and far-left lanes of the corner (Zone K, F). This condition is due to aggressive lane invasion maneuvers where those with the right of way are not accustomed to these violating behaviors. In the case of maneuvers at four-legged intersections, it was evident that left turns in the opposite direction start lane invasion earlier from the intersection's exit, resulting in complications with vehicles that want to exit the intersection in the nearby lane. Finally, at this intersection, direct crossings pose a higher risk of conflict at the ends of the crossing, either by initiating or completing the maneuver, because they accelerated to access the intersection or found higher speed or opposing lane displacement in the opposite lane while completing their entrance.

According to the findings of this study, motorcyclists face visibility problems, particularly near corners, when entering intersections, which can increase PET risk values. These problems can include poor or obscure left visibility caused by roadside obstructions, improper construction, such as stalls for street vendors, and corner obstructions, such as billboards and advertising. Ensuring good visibility is essential, especially at corners near intersections where a "clear sight triangle" or intersection sight distance (ISD) is required from the main road access (AASHTO 2010). The left turn is critical for visibility since it requires yielding the right-of-way to vehicles in the near and opposite lanes, making it the most challenging turn for motorcyclists. Corners with poor visibility may encourage motorcyclists to move ahead to cross at the intersection. Most motorcycle riders intend to maneuver ahead of other traffic at intersections (Promraksa, et al. 2022).

Motorcyclists with a risky attitude were more at risk of road conflicts. Risky movements are experienced as aggressive acts by motorcyclists seeking to prevail over other road actors and sensation-seeking, as noted by Cheng, et al. (2010) and Tunnicliff, et al. (2012). This behavior was deemed risky when the motorcyclist displayed signs of acceleration and anxiety upon entering, lifted the motorcycle on one wheel (wheelie), made rapid or abrupt movements on the handlebars, over-accelerated, violated the right of way, overlapped the motorcycle, or applied sudden braking (stoppie). Motorcyclists with these behaviors are very likely to violate the right of way of other vehicles (Abdul Manan, et al. 2015).

In this study, one of the high-risk behaviors among motorcyclists was making a left turn by encroaching on the opposite lane, also known as an indirect entrance. This behavior can be hazardous, as the riders try to take advantage of the opposite lane to reintegrate into the correct lane, often resulting in risky maneuvers. In many cases, this behavior is due to the impatience of motorcyclists in waiting for their turn to enter the lane correctly (White, et al. 2002). As a result, during the indirect entrance maneuver, motorcyclists require sudden and excessive acceleration to return to their original lane and avoid a collision (Chen et al., 2022). This type of maneuver was also identified in studies previously developed in Malaysia (Abdul Manan, et al. 2015).

In general, the rate of severe conflicts per hour identified by motorcyclists was high in consideration with referent studies in LMIC, such as those developed by Abdul Manan (2014), Uzondu, et al. (2019) and Paul, et al. (2020). The implementation of observational analysis and road conflict techniques supported by road safety surrogate measures allowed a global analysis of motorcyclists' interactions in the access from the intersection to the main road. The PET indicator was used to develop the risk analysis as recommended by the literature due to its reliability in its measurement of conflicts at intersections, where only times are calculated from the crossing between two road actors supported by the frames on the video recordings (Hydén 1996, Mahmud, et al. 2017).

Finally, one of the limitations of this study was its univariate approach, which may not have accounted for potential correlations or interactions among the investigated factors. This limitation highlights an interesting avenue for future research, where multivariate analysis, data mining, and machine learning techniques could explore potential interactions and generate new insights or predictions.

5. Conclusions

By detecting a set of unsafe characteristics and behaviors exhibited by motorcyclists when attempting to access intersections, the present study has revealed that motorcycles demonstrate a higher incidence of severe traffic conflicts in both intersections than other motorized vehicles. Specifically, the rate of such events is approximately three times higher in these circumstances. In addition, it was found that infrastructure conditions significantly impact the risk of intersection conflicts. For example, poor visibility to the left increased the risk of traffic conflicts for motorcyclists. Further analysis of traffic flow conditions revealed that intersections with vehicle flows of<10,000 vehicles had a greater risk of severe traffic conflicts. Among motorcyclists, right turns were found to be the most common intersection conflicts. Also, it was determined through analysis of the Post Encroachment Time (PET) that the most unsafe maneuver was the indirect left turn into opposing traffic. Regarding the individual behaviors of motorcyclists, aspects such as not stopping at intersections and driving recklessly increased the risk of traffic conflicts among motorcyclists.

This study had the benefit of capturing information related to behavior, traffic interactions, and traffic conflicts to analyze safety conditions, mainly for vulnerable actors such as motorcyclists, and thus identify unsafe actions without waiting for road crashes. As part of the recommendations, it is advisable to consider improving infrastructure in aspects such as visibility and signaling. Additionally, promoting demarcation in the proximity of intersections (access and main road) and implementing separators such as milestones, speed bumps, or bollards should be considered. These elements have shown their benefit in preventing lane invasion and wrong-way driving, reducing travel speed and traffic conflicts for motorcycles (Hsu, et al. 2019).

Compliance with Ethical Standards

The study is not funded by any agency. The authors do hereby declare that there is no conflict of interest with other works regarding the publication of this paper. This article does not contain any studies with human participants or animals performed by any author.

CRediT authorship contribution statement

Holman Ospina-Mateus: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Software, Visualization, Writing – original draft. **Leonardo Quintana Jiménez:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Francisco J. Lopez-Valdes:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

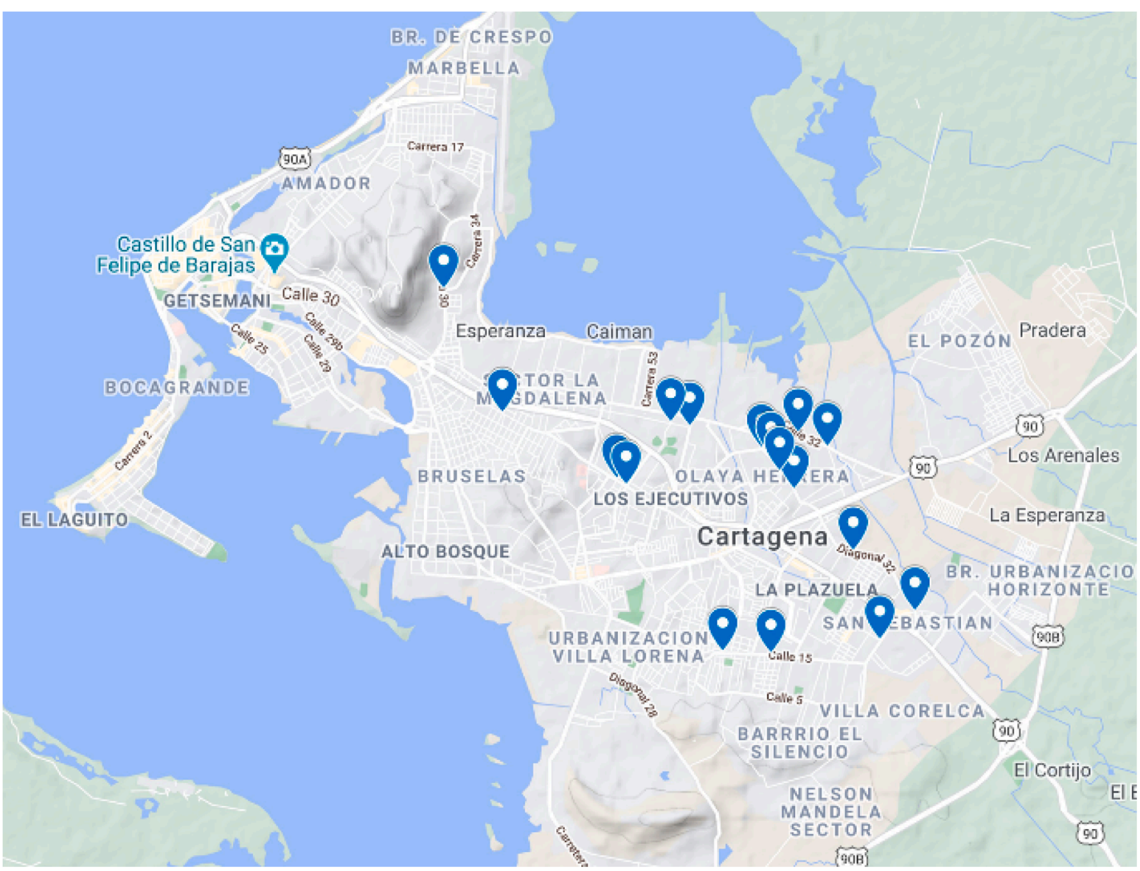
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Appendix 1. Location of observation points at intersections: 10 locations for the three-legged intersections and 7 locations for the four-legged intersection.



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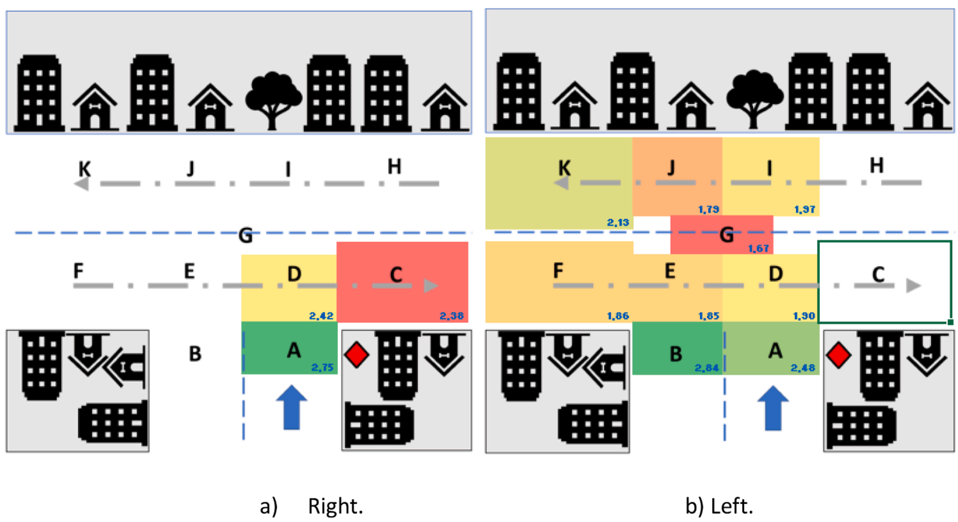
Appendix 2. The contrast between turning maneuvers and visibility at three-legged Intersections.

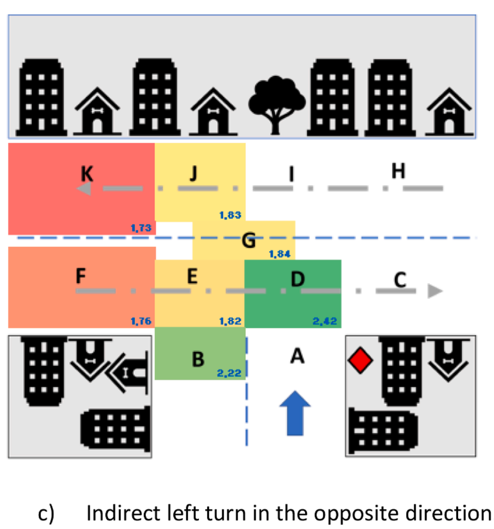
Turning maneuver	Type of visibility	PET Right Visibility N	Average	S.D	P-Value [a]	Left Visibility N	Average	S.D	P-Value [a]
Right	Clear	627	2,37	0,90	0,14	511	2,53	0,94	0,15
	Poor or obscured	512	2,45	0,92		628	2,45	0,90	
Left	Clear	428	1,81	0,86	0,21	426	1,89	0,93	0,16
	Poor or obscured	503	1,88	0,83		505	1,81	0,78	
Indirect left turn	Clear	57	1,70	0,75	0,23	66	2,12	0,87	**0,03***
in the oppositedirection	Poor or obscured	290	1,83	0,76		281	1,86	0,83	

a. *t*-test for comparison between types of visibility (clear or poor). * Statistically significant difference according to *t*-test ($p < 0.05$)

Appendix 3. PET value by areas of the intersection according to the turning maneuvers of the motorcycle access at three-legged Intersections.



a) Right. b) Left.



c) Indirect left turn in the opposite direction.

Appendix 4. The contrast between turning maneuvers and visibility at four-legged Intersections.

		PET							
Turning maneuver	Type of visibility	Right Visibility N	Left Visibility Average	S.D	P-Value [a]	N	Average	S.D	P-Value [a]
Right	Clear	148	2,52	0,85	0,73	393	2,57	0,93	0,24

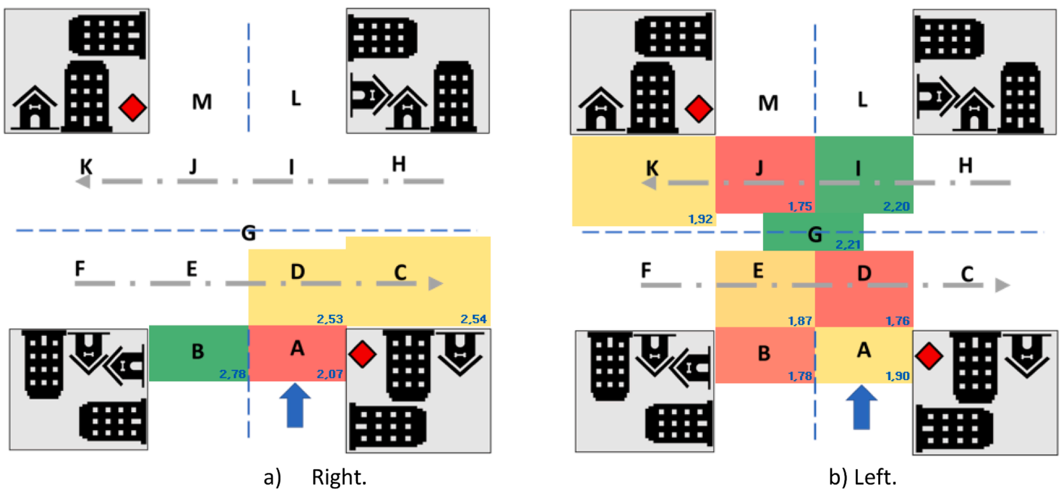
(continued on next page)

(*continued*)

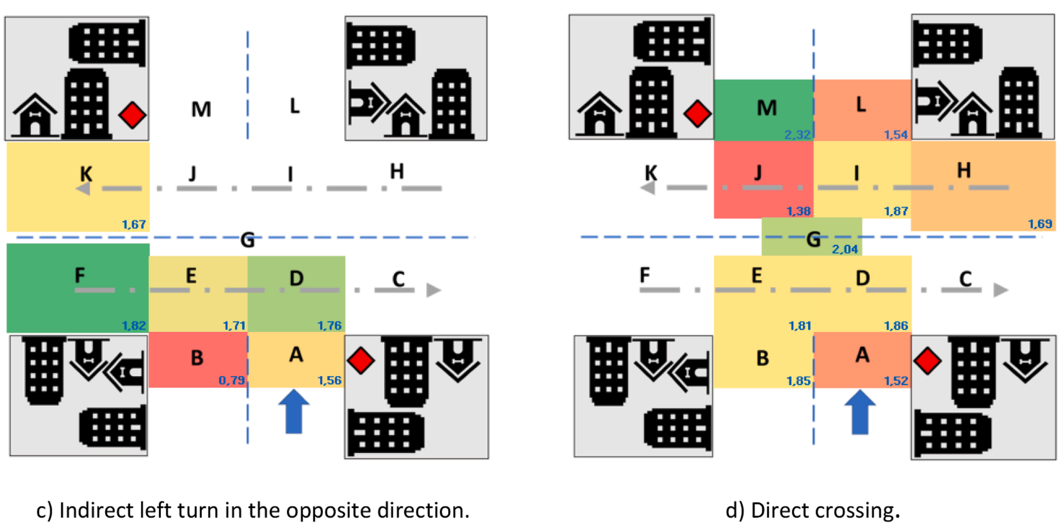
		PET							
	Poor or obscured	516	2,54	0,91		271	2,49	0,84	
Left	Clear	81	1,94	0,66	0,40	224	1,86	0,66	0,27
	Poor or obscured	305	1,87	0,68		162	1,93	0,69	
Indirect left turn in the oppositedirection	Clear	39	1,89	0,71	0,15	161	1,80	0,66	**0,04***
	Poor or obscured	212	1,71	0,63		90	1,63	0,60	
Direct crossing	Clear	265	1,85	0,68	0,85	242	1,87	0,79	**0,03***
	Poor or obscured	337	1,87	0,78		360	1,74	0,70	

a. *t*-test for comparison between types of visibility (clear or poor). * Statistically significant difference according to *t*-test (p < 0.05)

Appendix 5. PET value by areas of the intersection according to the turning maneuvers of the motorcycle access at four-legged Intersections.



a) Right. b) Left.



c) Indirect left turn in the opposite direction. d) Direct crossing.

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