Crosswalk Safety evaluation using a Pedestrian Risk Index as Traffic Conflict Measure

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ABSTRACT

More than 14% of the approximately 25,000 people killed each year in traffic accidents in Europe are pedestrians.

This high proportion of pedestrian fatalities led transportation researchers to make the improvement of pedestrian safety a priority. Few performance models based on crash data for pedestrian crashes exist. This is due to the spread distribution of the data that make difficult identifying statistical correlations. Traditional reactive strategies based on crash history analysis depend greatly on the quality and availability of the crash data. Consequently surrogate safety measures were developed as an efficient preventive approach.

The Traffic Conflict Technique (TCT) was developed as "surrogate measure of road safety" by using near-accident indicators based on the measurement of the spatial and temporal proximity of road users. In this paper, a new conflict indicator, named Pedestrian Risk Index (PRI), is proposed, linking both the probability of collision between vehicle and pedestrian and the severity of the consequences.

A before-after evaluation was carried out as a case study in Spain using PRI as a surrogate measure of safety in order to evaluate the safety performance of new traffic calming devices that replace zebra marked crosswalks.

This paper shows that PRI is an effective measure of modifications in drivers' behavior due to the installation of different safety countermeasures at a crosswalk. The PRI shows a reduction in severity of conflicts with an expected propensity to improve pedestrian safety.

Keywords: safety, pedestrian, crosswalk, traffic conflict

INTRODUCTION AND BACKGROUND

Traffic safety is commonly analyzed in terms of the number of traffic crashes and human losses. This approach is regarded as 'reactive', implying that a significant number of accidents must be recorded before a decision can be made. A further drawback with this approach concerns the quality and availability of accident data.

This has led to increasing interest in obtaining surrogate measures that reflect the safety of a road facility.

To be useful, a surrogate measurement technique should satisfy two conditions *(3)*:

1. A measurable or observable non-crash event that is physically related in a predictable and reliable way to actual crashes, and

2. A practical method for converting or calibrating the non-crash event into the corresponding crash frequency and/or severity.

Most literature in surrogate measures is related to the Traffic Conflicts Technique (TCT) *(4, 5, 6, and 7)*. TCT is a methodology for field observations based on measures of the spatial and temporal proximity of road users (proximal safety indicators) that describe the interaction between road users involved in a critical event for safety.

A conflict is so defined: *"A traffic conflict is an observable situation in which two or more road users approach each other in space and time to such an extent that there is risk of collision if their movements remain unchanged"(5)*.

The primary advantage of TCT is that conflicts occurred much more frequently than crashes. Furthermore TCT may provide information on relative risks to diagnose the types of problems at a particular location, and it represents an easy and efficient tool to check location safety issues when there is limited or no crash data.

The predictive validity of the TCT is most often determined by the level of statistical correlation between observed conflicts and accident data. Chin and Quek *(4)* suggested that validity problems were at least partially due to the quality and coverage of accident data. Hydén *(5)* also pointed out the need for validation in relation to the diagnostic qualities of the Traffic Conflict Technique instead of the more typical approach that was mainly directed at establishing predictive ability. Furthermore, Migletz *(6)* and Svensson *(7)* indicated that conflict studies can produce estimates of accident occurrence that are as good as those based on accident data, but requiring a significantly shorter period for data collection.

The reliability of conflict measures can be improved by the use of objectively defined measures, for example, through processes involving video-analysis.

Although largely developed in the case of conflicts between vehicles, TCT presents some gaps when pedestrians are involved in the conflict. This may be due to the complex movement dynamics and groupings, non-rigid, and generally less organized nature of pedestrian traffic.

In TCT literature, attempts have been made to define spatial or temporal indices of the severity of vehicle-pedestrian conflicts. Among these, there is the Time to Zebra (TTZ), proposed *(8)* as a variation of the concept of Time to Collision *(9)* and developed to estimate the frequency and severity of a critical situation between a vehicle and the pedestrian.

The Post Encroachment Time (PET) between two road users, defined by Allen *(10)*, can also be used. The PET is defined as the period of time from the moment when the first road user leaves the conflict area until the second road user reaches it. Usually, the last calculable PET (last PET) is taken as a figure to evaluate traffic safety. Hupfer *(11)* proposed the DST (Deceleration to

Safety Time), that is the necessary deceleration so that second road user reaches the conflict area not earlier than the first road user leaves it (i.e. when last PET =0, there is DST_0).

In this context, the Pedestrian Risk Index (PRI) was proposed as a new conflict indicator. It is a TCT measure for pedestrians and is appropriate for different traffic situations.

Although, the mechanical formulas used to define PRI are well known and the analytic approach to characterizing the kinematics of vehicle/pedestrian conflict appears to be treated by other authors *(12, 13, 14, 15, 16, and 17)*, in this paper it is shown how to compute an index derived by the actual driver behavior basing on the TCT approach. Therefore, the main difference from the studies reported in literature is that PRI is carried out using actual driving behavior observed at the zebra crossing during the entire development of the traffic conflict phase defined by the authors.
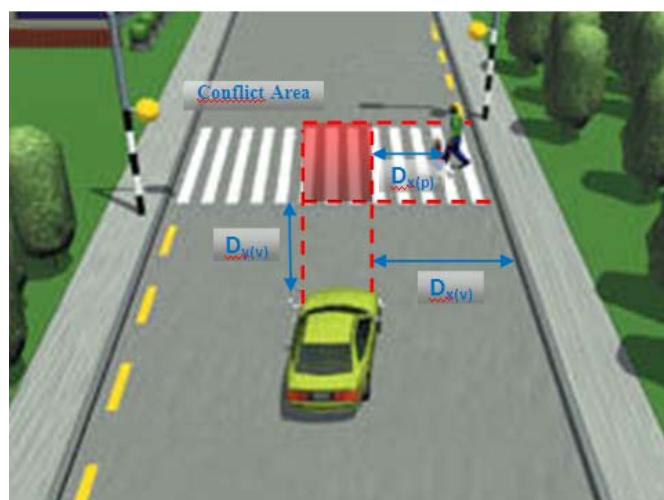
PEDESTRIAN RISK INDEX (PRI)

PRI is an indicator of the type "if…then" to evaluate the probability and potential severity of a pedestrian-vehicle collision.

In the dart-out crash model, in which a car is traveling when the pedestrian begins moving toward the street, it was assumed that if it is possible to pass the conflict area before the pedestrian, this is what the driver does. Otherwise, if the pedestrian reaches the conflict area before the vehicle, the pedestrian stops (Figure 1).

Based on this model, three different phases of the conflict can be identified:

1. Passing phase: the vehicle is so close to pedestrian crossing that it can overtake the conflict area before the pedestrian reaches it. Otherwise, the vehicle is so far that the pedestrian can cross before the vehicle
2. Stopping phase: the vehicle is so far and with a speed that it can stop in safety in the possibility of pedestrian presence in conflict area;
3. Conflict phase: the positions and speeds of the two road users can lead to collision if conflict actors don't take an evasive maneuver (according to conflict definition);

Particularly, phase 3 has to be identified and analized carefully because it represents the condition of potential collision between vehicle and pedestrian.

FIGURE 1 Conflict representation.

For each instant of the conflict (FIGURE 1), three variables of time can be defined:

- Time to Collision of the vehicle, obtained from following equation:

$$TTC_i = \frac{D_{yi(v)}}{V_{i(v)}}$$

(1)

where:
$TTC_{i(v)}$ [sec] : vehicle time to reach the pedestrian crossing at instant *i*.
$D_{yi\,(v)}$ [m] :longitudinal distance between the vehicle and the crossing at the instant *i*.
$V_{i(v)}$ [m/sec] : vehicle speed at the instant *i*.
- Time to Collision of pedestrian is carried out in order to establish if a pedestrian can arrive at the conflict area in time to collide with vehicle.

$$TTC_{pi} = \frac{D_{xi(v)} - D_{xi(p)}}{V_p}$$

(2)

where:
$TTC_{i(p)}$ [sec] :pedestrian time to reach conflict area, at instant *i*.
$D_{xi\,(v)}$ [m] : lateral vehicle distance at instant *i*.
$D_{xi\,(p)}$ [m] : pedestrian position on crossing at instant *i*.
V_p [m/sec] : pedestrian speed.

- Vehicle time to stopping (T_s), carried out using the following equation:

(3)

$$T_{si} = T_r + \frac{V_{i(v)}}{a_b}$$

where:
T_{si} [sec] : stopping time instant i.
T_r [sec] : reaction time of the driver.
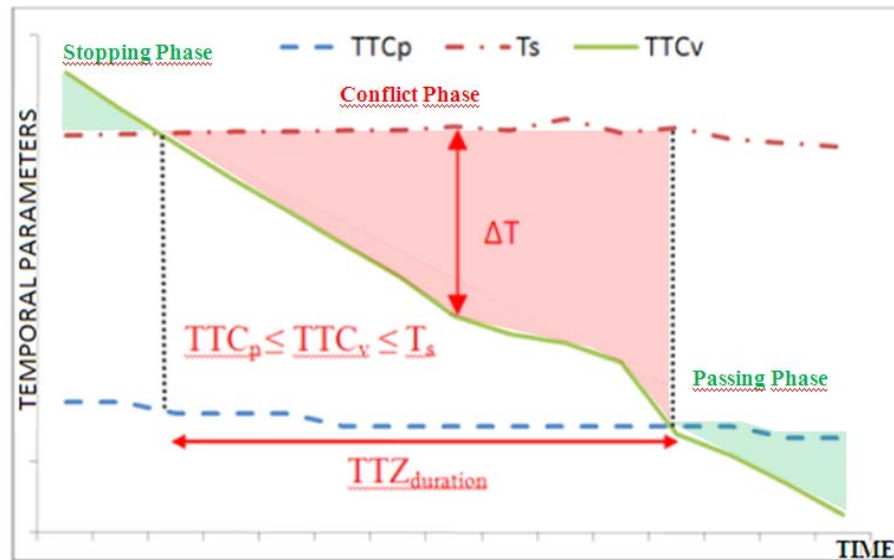$V_{i(v)}$ [m/sec] : vehicle speed at instant *i*.
a_b [m/sec^2] : braking deceleration (absolute value).
These time variables are utilized to define conflict:
- when $TTC_v > T_s$, the vehicle can safely stop before the conflict area (stopping phase);
- when $TTC_v < TTC_p$, the pedestrian reaches the conflict area only after the vehicle has passed (passing phase).
- when $TTC_v < T_s$, the vehicle can't stop before to reach the conflict area;
- when $TTC_v > TTC_p$, the pedestrian is exposed to conflict with vehicle
$TTZ_{duration}$ (Time To Zebra duration) is defined the conflict time (conflict phase) in the interval:
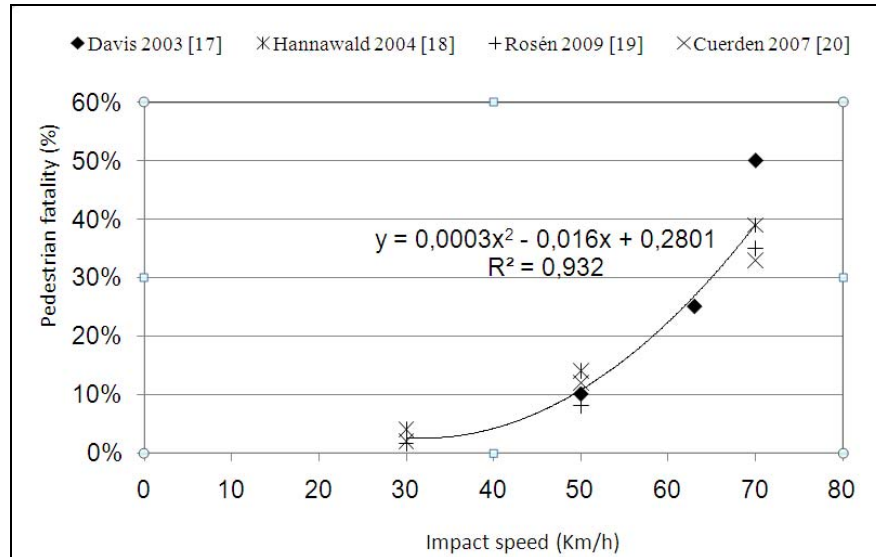$TTC_p < TTC_V < T_s$ (FIGURE 2).

FIGURE 2 – Temporal parameters TTCp, Ts and TTCv vs. Time. Identification of Potential conflict time (TTZ$_{duration}$).

The difference ΔT_i, between the Time to Stopping (T_s) and the Time to Collision (TTC_v) at instant i, is a measure of the chance to make a safe emergency stop. Therefore it can be considered a surrogate measure of the probability that the collision between vehicle and pedestrian occurs.

Regarding the severity of the conflict, previous studies using real-world accident data *(16, 18, 19, 20)*, determined that injury severity among pedestrians strongly depended on the impact speed (Figure 3). Basing on these studies, at 70 km/h of impact speed there is approximately a 40 percent chance of fatal injury for a pedestrian hit by a vehicle (Figure 3).

Although other studies report a 50% chance of fatal injuries at 53 km/h by Pasanen *(14)*, at 45 km/h by Anderson *(21)* or at 52 km/h by Ashton *(22)*, they focused on the form of the correlation between impact speed and severity rather than on the value of the probability for pedestrian fatality, it can be assumed that the correlation between probability of pedestrian fatality and impact speed (V_{impact}) follows the second power law (FIGURE 3).

FIGURE 3 Summary of previous study on the risk of pedestrian fatalities in relation to impact speed.

Basing on this assumption, in order to take into account the collision severity the impact speed (V_{impact}) is included in the formulation of PRI supposing a braking deceleration.

From uniformly accelerated motion law, the formulation of V_{impact}, at each instant of the conflict phase, is:

$$V_{impact} = \sqrt{V_v^2 - 2 \cdot a_b \cdot (Dy - V_v \cdot T_r)} \qquad (4)$$

where:
V_{impact} [m/sec] : collision speed at instant i
V_v [m/sec] : initial vehicle speed at instant i,
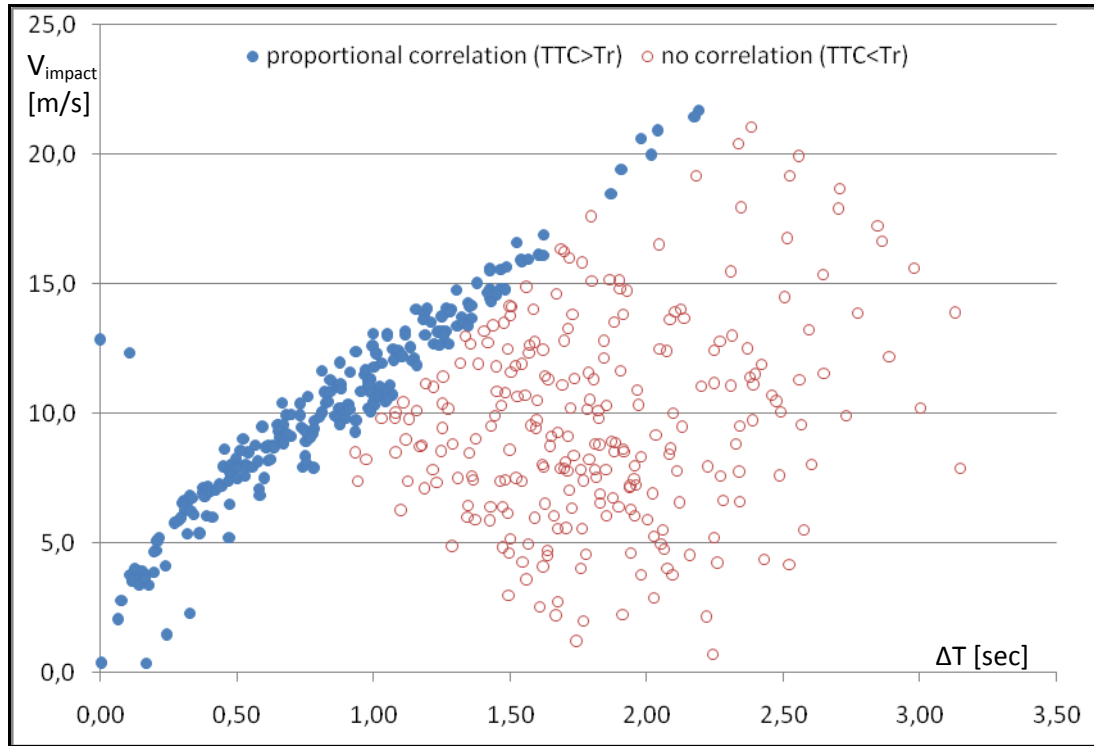a_b [m/sec^2] : breaking deceleration,
$D_{y(v)}$ [m] : longitudinal vehicle distance from the conflict area,
T_r [sec] : perception and reaction time of the driver.
$V_v \cdot T_r$ [m] : distance travelled during the perception and reaction time.

To evaluate the formulation of PRI taking into account both Δt, as measure of conflict probability, and V_{impact}, as measure of conflict severity, a correlation analysis of the two factors was carried out. Using data collected for the present case study, Δt and V_{impact} values were registered during several conflicts and plotted in FIGURE 4.

From FIGURE 4 one can observe that during the former part of the conflict phase 2, when TTC_v is higher than the reaction time, a strong correlation exists between Δt and V_{impact}. In the latter part of the "conflict phase" (phase 3), when TTC_v is less than the reaction time, no correlation exists between Δt and V_{impact}. Therefore to respect the square low between V_{impact} and severity (FIGURE 3), V_{impact} should be introduced in PRI formulation if the correlation hypothesis is accepted, otherwise V^2_{impact} if no correlation is considered.

FIGURE 4 V_{impact} Vs. ΔT during the conflict phase

Therefore, to emphasize the role of the impact speed V^2_{impact}, was introduced in the Pedestrian Risk Index formula:

$$PRI = \sum\nolimits_{TTZ_D} \left(V^2_{impact_i} \cdot \Delta T_i \right) \tag{5}$$

where:

$V_{impacti}$ [m/sec] : potential collision speed at the instant *i*

ΔT_i [sec] : difference between the T_{si} and TTC_{vi} (FIGURE 2).

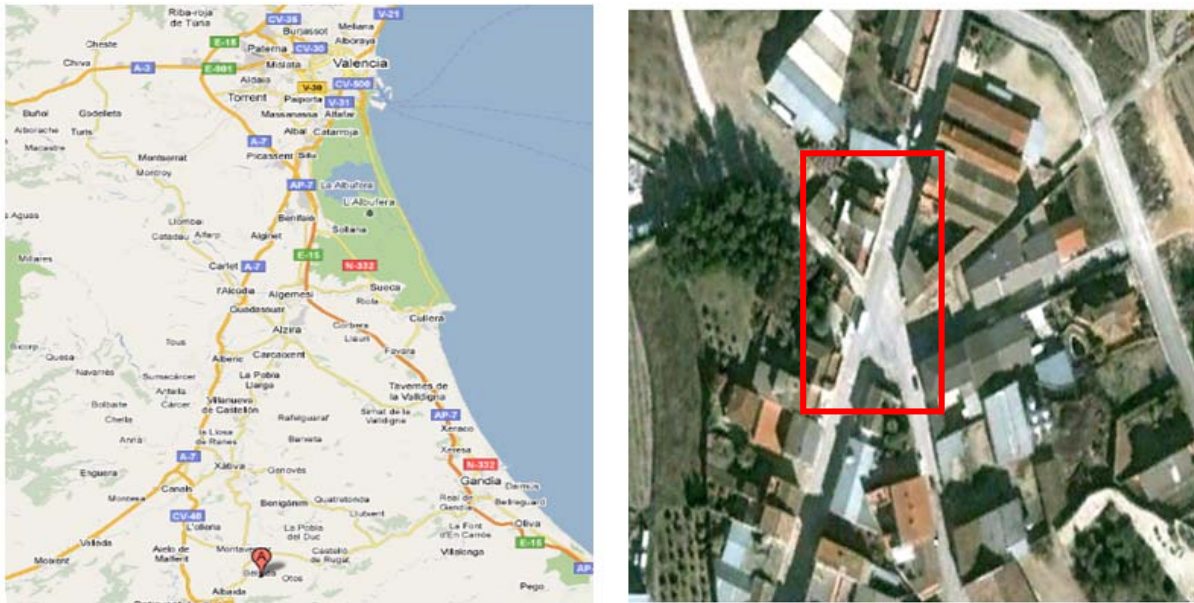This formulation of PRI, considering both the probability of collision (ΔT) and the severity (V_{impact}), satisfies the definition of a risk index.

CASE STUDY

A case study was carried out in a cross-road of the town of Bélgida (Valencia, Spain) where two pedestrian crossings are placed at a four legs intersection (FIGURE 5).

Traffic calming improvements had been implemented in different stages on the main road, as a part of the research project called MODETRA "Methodology for the design and implementation of traffic calming devices".

FIGURE 5 Site on study.

This "progressive" before-after study was developed during four phases of the intervention, starting from the original situation (0-configuration) and progressing to the more complete configurations with speed humps and raised crosswalks (speed tables).

Scenarios

First scenario (North 1 & South 1)
The initial configuration included two zebra crossings in a bad maintenance condition with poorly visible marking. Video recording was taken on April 3th 2009 between 9:00 and 13:00, in order to avoid traffic flow congestion (FIGURE 6).

FIGURE 6 Southern (A) and Northern (B) Crosswalk in the first scenario.
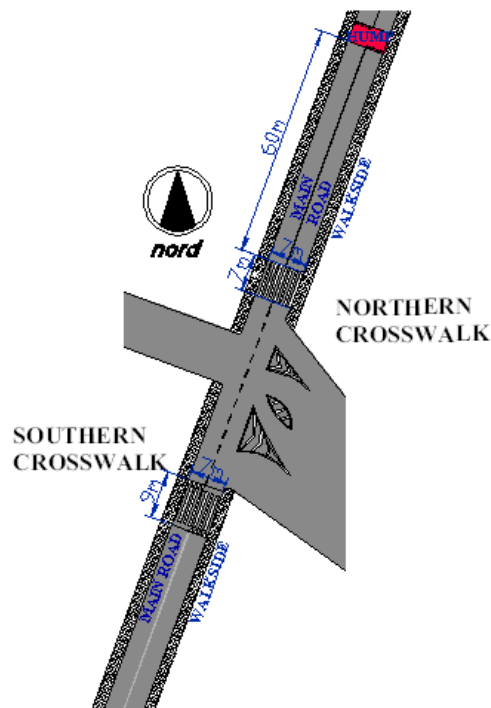
Second scenario (North 2 & South 2)
The first intervention regards the marking of zebra crossings without any speed calming improvement. The crosswalk marking was made on April 9th 2009 and the videos were taken between 9:00 and 13:00 on April 28th 2009 (FIGURE 7).

FIGURE 7 Southern (A) and Northern (B) Crosswalk in the second scenario.

Third scenario (North 3 & South 3)
In the third phase the two crossings are implemented with different traffic calming interventions. A speed hump with maximum height of about 6 cm, was set 60 meters before Northern crosswalk, while in other direction a raised crosswalk was placed in correspondence of the other zebra crossing (South) (FIGURE 8). The speed table was built with a maximum height of about 10 cm and ramps slope of 1:20, for a top dimension of 7 m in width and 9 m in length.
The intervention was made on July 2nd 2009 and video recording on July 15th 2009, in the same temporal interval of previous ones.

FIGURE 8 Southern and Northern Crosswalk in the third scenario.

Fourth scenario (North 4 & South 4)
The last improvement concerns the setting of a prefabricated raised crosswalk on the Northern zebra crossing that is combined with the speed hump realized in the previous step (FIGURE 9). The maximum height of this table is of 7.5 cm for a length of 7 meters and width of 5.5 m. The ramps slope is 1:10.
The Southern one remains as in the third scenario with the addition of a prefabricated speed hump 200 m before it. This last video capture was on September 3th 2009, more than 30 days after the intervention. Analysis period was during the four hour interval between 9:00 and 13:00 a.m.

FIGURE 9 Southern (A) and Northern (B) speed tables in the fourth scenario.

Data collection and treatment

Video processing was used in order to extract, with a step of 0.2 sec, all the conflict parameters (time and distance) necessary to carry out PRI. In order to make a detailed survey of the area, the video recording system consisted in up to 6 digital cameras installed on a Mobile Traffic Laboratory developed by the Highway Engineering Research Group (HERG) of the Universidad Politécnica de Valencia (Spain).
Mobile Traffic Laboratory is an articulated platform which can be raised up to 12 m high. Cameras are installed on the highest point of the platform. Focus and zoom of these cameras is controlled from a laptop in real time by means of a wireless network.
The location of the cameras is not visible to the drivers in order to not influence their behavior and allows a sufficiently wide zone of over-position to have a redundancy of elements (visibility of a point at least in two captured videos). All the surveys were carried out in daytime and good weather conditions.
Trajectories of each approaching vehicle and pedestrian are obtained on a two-dimensional coordinate system. This was made with specific software developed by the HERG. Several applications of this software have been already presented *(23)*.
From the sequence of the video frames, it is possible to extract positions and speeds of the vehicle to calculate the time variables characterizing the PRI during the conflict phase.
For the present application it was considered appropriate to choose a value of a reaction time, T_r, of 1.07 sec, as well as an average deceleration of 5.4 m/sec². These values are chosen with reference to the average of the statistical distributions *(24)* that were carried by tests of

emergency stop to avoid an obstacle appearing suddenly in the roadway. Moreover, this study adopts a pedestrian crosswalk walking speed value of 1.2 m/s *(25)*. These values can be easily modified if different conditions are evaluated or to carry out a sensitivity analysis.

To uniform the PRI estimate, the only considered vehicles are passenger car and LGV (Light Goods Vehicle). The powered two wheels (PTW)users are excluded from analysis, because of their aggressive behavior, in approaching pedestrian crossing *(2)*.

The extracted data concern the situation of a free flow condition for vehicles (isolated vehicle) with and without the presence of a visible pedestrian on sidewalk, just waiting to walk on pedestrian crossing.

ANALYSIS OF RESULTS

For the different crosswalk scenarios, the traffic conflicts were detected and the corresponding Pedestrian Risk Indices were carried out in order to evaluate the effectiveness of the safety improvements and the sensitivity of the new proposed indicator to identify change in driver behavior due to modifications on site configuration. TABLES 1 and 2 show the mean (μ) and standard deviation (σ) of PRI statistics for the different scenarios.

TABLE 1 Means and Standard Deviations of PRI in the Four Configurations in Northern Crosswalk

		Scenario 1 [North_1]		Scenario 2 [North_2]		Scenario 3 [North_3]		Scenario 4 [North_4]	
		Sample	PRI	Sample	PRI	Sample	PRI	Sample	PRI
North->South without Pedestrian	μ	60	1992,9	32	1623,7	40	407,0	38	161,2
	σ		1907,7		1293,3		298,7		210,2
North->South with Pedestrian	μ	38	2908,9	37	1506,2	35	351,2	37	121,2
	σ		2567,4		1216,0		181,4		97,4

TABLE 2 Means and Standard Deviations of PRI in the Four Configurations in Southern Crosswalk

		Scenario 1 [South_1]		Scenario 2 [South_2]		Scenario 3 [South_3]		Scenario 4 [South_4]	
		Sample	PRI	Sample	PRI	Sample	PRI	Sample	PRI
South->North without Pedestrian	μ	60	997,0	55	1275,9	30	332,9	32	261,5
	σ		1303,5		991,6		413,0		142,1
South->North with Pedestrian	μ	47	733,1	35	854,4	30	101,3	34	175,1
	σ		593,2		607,1		126,3		136,0

In order to verify the statistical significance of the differences between the averages values of PRI obtained in the different scenarios of pedestrian crossing, a Student t-test was conducted. Considering a level of confidence of 95%, if the P-value is less than 0.05, we can reject the null hypothesis (the case of equal mean) in favor of the alternative and, therefore we can consider the difference in the mean value of PRI as statistically significant (gray cells in TABLES 3 and 4). Also the F-test was carried out to accept the hypothesis of equal variance between analyzed

samples (TABLE 3 and TABLE 4). Based on F-test results the t-student for equal or different variance was carried out.

TABLE 3   F-test and Student T-test for Means Difference in the Four Configurations in Northern Crosswalk

scenario		NO PEDESTRIAN					WITH PEDESTRIAN			
		F-Test		T-Student			F-Test		T-Student	
	ΔPRI	F-ratio	P-value	T-value	P-value	ΔPRI	F-ratio	P-value	T-value	P-value
North_1 vs North_2	369,25	1,976	0,042	0,970	0,335	1402,76	4,157	0,000	3,031	0,004
North_1 vs North_3	1585,96	40,779	0.000	6,324	0,000	2557,71	200,265	0.000	6,125	0,000
North_1 vs North_4	1831,72	82,404	0.000	7,367	0,000	2787,76	695,416	0.000	6,689	0,000
North_2 vs North_3	1216,72	20,640	0.000	5,122	0,000	1154,95	48,176	0.000	5,486	0,000
North_2 vs North_4	1462,47	41,708	0.000	6,182	0,000	1385,00	167,290	0.000	6,638	0,000
North_3 vs North_4	245,75	2,021	0,034	4,219	0,000	230,05	3,472	0,000	6,651	0,000

TABLE 4   F-test and T-Student for Means Difference in the Four Configurations in Southern Crosswalk

Scenario		NO PEDESTRIAN					WITH PEDESTRIAN			
		F-Test		T-Student			F-Test		T-Student	
	ΔPRI	F-ratio	P-value	T-value	P-value	ΔPRI	F-ratio	P-value	T-value	P-value
South_1 vs South_2	-278,92	1,728	0,043	-1,298	0,197	-121,30	0,955	0,873	-0,907	0,367
South_1 vs South_3	664,10	9,959	0,000	3,601	0,001	631,74	22,059	0,000	7,055	0,000
South_1 vs South_4	735,51	84,087	0.000	4,326	0,000	557,98	19,025	0.000	6,213	0,000
South_2 vs South_3	943,02	5,764	0,000	6,143	0,000	753,04	23,108	0,000	7,160	0,000
South_2 vs South_4	1014,43	48,667	0,000	7,464	0,000	679,28	19,929	0,000	6,445	0,000
South_3 vs South_4	71,41	8,443	0,000	0,901	0,374	-73,76	0,862	0,691	2,209	0,031

Based on the obtained results and experimental scenarios, the following considerations about the effectiveness of the improvements can be highlighted:

　　　- The repainting of the Zebra did not show a significant reduction of PRI values.

- The use of traffic calming such as speed humps and speed tables reveals a considerable improvement in road safety conditions as demonstrate by lowest PRI values. Specifically, the configurations with tables present best effects in calming the behavior of road users compared with the presence of humps set before the pedestrian crossings.

- The sequence of a hump and a table doesn't imply remarkable benefits in front of solutions with only one facility or device.

In Tables 3 and 4: scenarios with different mean at 95% level of significance are highlighted in grey cells

Moreover, the vehicle driver doesn't seem to perceive the presence of a pedestrian waiting to cross on sidewalk as a limitation of his own maneuvering space. This outcome derives from T-student tests carried out in separate analysis, not reported in the present paper, showing no statistically significant differences in PRIs between "with pedestrian" and "no pedestrian" cases.

CONCLUSIONS

Traditionally road accident statistics are used to assess the level of road safety and to evaluate road safety programs. In some cases, the lack of good and reliable accident records can prevent proper analysis.

An alternative approach that overcomes this problem is the use of safety surrogates measures, like Traffic Conflict which rely on observations of critical traffic situations. An important advantage of TCT with respect to crash analysis is having a much larger sample on a much shorter period of observation.

Even though a statistical correlation between TCT indices and number of crashes is complex to define, the TCT is able to identify and evaluate operational deficiencies and improvements.

A new TCT index was proposed to analyze conflicts between vehicles and pedestrians. PRI is defined to evaluate the potential severity of a pedestrian-vehicle conflict, relating it both to severity and dangerousness of the traffic situation.

The application of the Pedestrian Risk Index method showed that this indicator is effective to highlight modifications in driver behavior due to safety improvements at a crosswalk.

Specifically in the case of the use of traffic calming devices such as speed humps and speed tables, the case study reveals a considerable improvement in road safety conditions. The configurations with speed tables present the best effects in calming the behavior of road users compared with the presence of humps set before the pedestrian crossings. The sequence of a speed hump and a speed table doesn't result in remarkable benefits compared to solutions with only one device.

Use of modern technology such as automated video-analysis techniques is shown to simplify, make faster and more accurate the Traffic Conflict analysis.

Even if a correlation between PRI and crash occurrence and severity is not available at this time, the analysis carried out in the present research, using a comparison among different scenarios, showed that PRI sensitivity to modification in driver behavior can lead to change in the probability and severity of a collision between a pedestrian crossing the road and an approaching vehicle. Therefore, PRI can be considered a "specific" risk factor. In order to compare different sites, an exposure factor must also be used to take into account the vehicle ($AADT_v$) and pedestrian traffic flow ($AADT_{ped}$) at the crossing.

Authors understand that the not proved correlation between PRI and the probability of collisions is a criticism of the paper. At pedestrian crossings usually zero or one pedestrian crashes occur

during the observation period, making it difficult to use crash counts as a comparison factor. Also the availability of good exposure measures, especially for pedestrian flow, is a recurrent problem. At this phase of our study the results confirm the sensitivity of the model to changes in the crossing configuration. The collection of crash data is still in progress and a study of correlation between PRI and crashes will be analyzed in the near future.

ACKNOWLEDGEMENTS

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