A SURROGATE VIDEO-BASED SAFETY APPROACH FOR VULNERABLE ROAD USERS IN THE LATIN AMERICAN CONTEXT

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Abstract

Walking and powered two-wheelers (PTWs) play a fundamental role in the urban mobility of many Latin American (LA) cities. Despite their importance, the road safety of these transportation modes, referred to as vulnerable road users, is still a major concern. In the Americas, pedestrians and PTWs represent almost half of the road fatalities as they account for 22% and 20% of the fatalities respectively. Moreover, the percentage of PTWs users in traffic fatalities has been rapidly increasing in Latin American countries - for instance, in Bogota, this increased from 18% in 2013 to 28% in 2017. To deal with the road safety problem, many developed countries have established programs and methodologies for the countermeasure implementation (e.g. "vision zero"). However, such programs are often absent in LA countries. Among many other factors, this is attributed to the lack of economic resources, safety-related data and tools for safety diagnosis and evaluation. Road crash data frequently does not exist or lacks quality. Crash data often suffers from inconsistencies, misclassification, inaccurate geographical locations and inaccurate identification of crash contributory factors. In addition, it can take years to gather sufficient information for diagnosis and countermeasure evaluation, making it difficult to determine failure mechanisms that lead to crashes and contributing risk factors. In this context, there is a need for data and methodologies for safety analysis and countermeasure evaluation that do not rely on crashes.

To address the issues with observed crash data, alternative approaches have emerged in the last few years. This includes the surrogate-road-safety approach which includes conflict techniques or measures of proximity and speed measures derived from video trajectory data. This alternative approach is a low cost and time efficient way to get data for safety diagnosis and evaluation of countermeasures. Despite the recent developments in surrogate safety measures and tools, very few studies exist in the literature regarding the investigation of vulnerable road users (VRUs) road safety in developing countries using alternative surrogate safety methods. Very little is documented about the contributing factors related to dangerous vehicle-VRUs interactions and the

low-cost road-design treatments that can help reduce VRUs injuries in LA context. As walking and PTWs are essential modes of transportation in LA countries, PTW face a great risk of injury and are involved in a disproportionate number of vehicle collisions in urban areas.

The general objective of this thesis is to introduce the use of surrogate measures of safety and methodologies for VRUs in the context of LA using video analysis techniques. More specifically, the first part of this research (Chapter 3) has two objectives. First, this thesis proposes and implements a proactive surrogate safety methodology using video trajectory data in the context of developing countries to identify risk-contributing factors to vehicle-pedestrian interactions at distinct types of junctions and to evaluate the effectiveness of temporary low-cost countermeasures using Cochabamba and Bogota as case studies. In the second half, extensive video trajectory data was obtained, automatically processed and used to analyze the effect of speed, conflicts and driver behavior, including maneuvering and traffic violations, on PTWs safety and to identify the factors contributing to PTWs risk in the LA context. Hundreds of hours of video data were automatically processed using a specialized computer vision software to generate speed and road-user trajectory data to investigate the risk factors. It is found that PTWs (with respect to other vehicle types), movement type and traffic circles (with respect to other intersection types) are among the key factors related to pedestrian surrogate safety outcomes. Moreover, from the two treated intersections, it is found that low-cost temporary treatments were effective at four-leg intersections but not at old traffic circles. We also found that PTW users (compared to other road users) have the highest operating speeds with a high rate of traffic violations and dangerous maneuvering behaviors. PTWs are faster when interacting with pedestrians and cyclists and the most dangerous type of PTWs are smaller mopeds and scooters. This research demonstrates the applicability of the proactive surrogate methodology based on automated video analytics in the Latin American context, where traditional methods are challenging to implement and that the proposed methodology could help evaluate temporary treatments in a short time period before they are permanently implemented and replicated.

Résumé

La mobilité urbaine en Amérique Latine se base fondamentalement sur la marche à pieds et les deux roues motorisés DRM. Mise à part l'importance des deux derniers, la sécurité routière de ces moyens de transport représente une vulnérabilité assez remarquable par leurs utilisateurs. Cela s'impose en tant que problématique majeure dans les pays concernés. Le taux d'accident que provoque la marche à pieds ou les DRM représente à peu près la moitié du taux d'accidents sur le continent Latino-Américain selon des statistiques établit en 2015 par l'organisation mondiale de la santé qui déclare que 22% des accidents routières émanent des piétons tandis que 20% font partie des DRM. Le pourcentage des accidents commises par les DRM augmente de fur et à mesure de sorte qu'il est arrivé de 18% en 2013 jusqu'à 28% en 2017 en Bogota. Pour résoudre les problèmes de sécurité routière, plusieurs pays développés ont établi des programmes et des méthodologies de mise en œuvre des contre-mesures ex : vision zéro. Malgré cela ces programmes sont quasi inexistants dans les pays latino-américains. Parmi plusieurs facteurs le manque des capacités économiques représente l'élément essentiel de l'absence de routes sécurisées, suite à l'absence des données nécessaires ainsi que les moyens de sécurisation diagnostique et d'évaluation. Ainsi que les données existantes sont souvent de mauvaise qualité. Elles subissent encore de l'incohérence, du mal classement, de mauvaises localisations géographiques, des mauvaises identifications des accidents, des facteurs contributifs. En plus ça pourra prendre des années pour réunir suffisamment d'information pour analyser et contre mesurer une évaluation ce qui rend difficile la détermination des échecs des mécanismes qui mènent à des crises et qui créent des risques. Dans ce contexte il y aura un besoin de donnés et de méthodologies pour les analyses de sécurité les contre-mesures d'évaluation qui ne basent pas sur les accidents.

En objectif de rendre compatible ces issus avec les données d'accidents surveillé, des approches alternatives sont apparues durant les dernières années en ayant comme exemple le substitut de la sécurité routière. Cela consiste des conflits techniques ou des mesures de proximités et de vitesse issus des données vidéo. Cette approche alternative représente un avantage de diminution de coût

ainsi que l'accélération du temps d'obtention des données pour diagnostiquer les mesures de sécurité ainsi que l'évaluation des contre-mesures. Malgré le développement des mesures et des outils de sécurité, peu d'études existent dans la littérature qui s'intéresse à la vulnérabilité des utilisateurs des routes. Malgré les développements majeurs dans les alternatives de la sécurité routière. Il n'existe pas beaucoup d'études d'enquêtes sur les utilisateurs vulnérables des routes UVR. Peu de documentation sur les facteurs liés au danger dû aux interactions des UVR et l'amélioration de la qualité des routes qui peut diminuer les accidentes menés par les UVR comme c'est le cas dans le modèle latino-américain LA. Alors que comme les marches à pieds et les DRM sont des moyens de transport essentiel aux pays LA. Les DRM affrontent des risques majeurs d'accident sur le niveau humain toute en provoquant des accidents de véhicules dans les zones urbaines.

L'objectif général de cette thèse est d'introduire l'utilisation de SMS et de méthodologies pour les UVR dans le contexte de LA utilisant des techniques d'analyse vidéo. Plus précisément, la première partie de cette recherche propose et met en œuvre une méthodologie proactive de sécurité routière de substitution qui utilise un outil d'analyse vidéo automatisé dans le contexte des pays en voie de développement afin d'identifier les facteurs contribuant au risque pour les interactions véhicule-piéton à différents types de jonctions et d'évaluer l'efficacité de contre-mesures temporaires à faible coût en utilisant Cochabamba et Bogota comme études de cas. Au cours de la seconde partie, de nombreuses données vidéo ont été obtenues, traitées automatiquement et utilisées pour analyser l'effet de la vitesse, des conflits et du comportement du conducteur, y compris les manœuvres et infractions au code de la route, sur la sécurité des deux-roues motorisés et identifier les facteurs contribuant au risque des deux-roues motorisés dans le contexte latino-américain. Des centaines d'heures de données vidéo ont été traitées automatiquement à l'aide d'un logiciel de vision informatique spécialisé afin de générer des données de vitesse et de trajectoire des usagers de la route dans le but d'étudier les facteurs de risque. Il a été constaté que les deux-roues motorisés (comparativement aux autres types de véhicules), le type de mouvement et les ronds-points (comparativement aux autres types d'intersection) font partie des facteurs clés influents sur la sécurité des piétons. De plus, à partir des deux intersections traitées, il a été constaté que les traitements temporaires à faible coût étaient efficaces aux intersections à quatre branches, mais pas aux anciens ronds-points. Nous avons également constaté que les utilisateurs de deux-roues motorisés (comparés aux autres usagers de la route) avaient les vitesses de fonctionnement les plus élevées, avec un taux élevé d'infractions au code de la route et des comportements de manœuvre dangereux. Les deux-roues motorisés sont plus rapides lorsqu'ils interagissent avec des piétons et des cyclistes, et les types de deux-roues motorisés les plus dangereux sont les cyclomoteurs et les scooters de petite taille. Cette recherche démontre l'applicabilité de la méthodologie de substitution proactive basée sur l'analyse vidéo automatisée dans le contexte latino-américain, où les méthodes traditionnelles sont difficiles à mettre en œuvre. Elle démontre également que la méthodologie proposée pourrait aider à évaluer les traitements temporaires dans un court laps de temps avant leur mise en œuvre et leur réplication permanente.

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Contribution of Authors

This thesis is a manuscript-based report consisting of the following journal/conference manuscripts. Details of the publications are presented below. I would like to declare that I am the sole author for this thesis. My contributions to this research include conducting the research studies, preparing the data, building the statistical models, analyzing the data, and writing the manuscript. My supervisor, Prof. Luis Miranda-Moreno, provided guidance, comments, and editorial revisions throughout the entire process. The co-authors of the publications helped in data collection, providing comments, and editing the papers.

Scholl, L., Elagaty, M., Ledezma-Navarro, B., Zamora, E., Miranda-Moreno, L., 2019. A surrogate video-based safety methodology for diagnosis and evaluation of pedestrian-safety low-cost countermeasures: The case of Cochabamba, Bolivia. Sustainability 11, 4737. https://doi.org/10.3390/su11174737

Elagaty, M., Miranda-Moreno, L., Scholl, L., Calatayud, M., Patino, J., 2019. Investigating Powered Two-Wheelers (PTWs) Risk Factors Using Automated Surrogate Safety Methods in Latin American cities. Manuscript submitted for a presentation at the TRB conference.

Elagaty, M., Miranda-Moreno, L.,2019. Investigating powered-two-wheelers (PTWs) risk factors using automated surrogate safety methods for developing countries: Case study of Bogota. TAC-ITS 2019 Canada Joint Conference, Halifax, NS presentation.

Scholl, L., Miranda-Moreno, L., Elagaty, M., Ledezma-Navarro, B., 2018. Identificación de factores de riesgos peatonales en intersecciones utilizando indicadores de seguridad vial sustituto en el contexto de países en desarrollo en Cochabamba, Bolivia. CLATPU 2018 Conference, Medellin, Colombia presentation by Scholl,L.

Chapter 1 Introduction

Despite the rapid growth in motorized traffic, an important proportion of the urban population in Latin American (LA) countries is unlikely to own a car (Roque and Masoumi, 2016). As a result, alternative transportation modes such as walking, motorcycling and transit play a key role. The popularity of alternative modes in Latin American countries can be related to many factors but affordability is a key one as wealthier households are more likely to rely on cars for mobility, while lower income households rely more on walking, biking, motorcycling and public transit (Guerra et al., 2018).

Walking is part of any trip, a way to access transit services, and a necessity for many people who do not have access to other modes of transport. Walking has a very important role for mobility in LA and developing countries. A study by the Development Bank of Latin America involving 29 cities in LA showed that 26% of trips were undertaken by walking, and 42% by public transport (CAF – Development Bank of Latin America, 2016). Moreover, in cities like Bogota, walking represents 20% of the modal split (Parra and Lemoine, 2017). In addition to walking and as an alternative to automobiles, the use of powered two-wheelers (PTWs) has dramatically increased in the last years. In Bogota, the PTWs market grew by 300% in just 10 years (Secretaría Distrital de Movilidad de Bogotá, 2017a). The usage of PTWs in urban transport is increasing in many low- and middle-income countries due to their affordability and high flexibility for travel. A survey conducted by the CAF – Development Bank of Latin America in five Latin American cities showed that 37% of PTWs users use them to earn money, 32% identified as PTW taxi passengers, and 31% own PTWs for private use. For the 37% using them to earn money, 58% used them as moto-taxis, 18% for deliveries and 24% as couriers and for other uses (CAF – Development Bank of Latin America, 2015). A study that aims at understanding the motivations of PTW users that lead to their increasing popularity in Latin America showed that PTWs are attractive due to their affordability and travel time efficiencies compared to congested auto traffic and deficient public transportation (Xaver et al., 2016). Additionally, increased ownership of PTWs in Latin American countries could be linked to lenient ownership regulations. Some countries like Argentina, Brazil, Colombia and Ecuador require prior training and an examination to obtain a license while others like Chile, Costa Rica, Paraguay and Uruguay only require an examination and in Mexico there is just a minimum age requirement (ITF-OECD, 2017) to own a PTW.

Despite the important role of walking and PTWs in the urban mobility in Latin America, the safety of these transportation modes is still a major concern. While the pedestrian road safety issue is not new, the PTWs safety issue is on the rise. Despite all the regions of the world experiencing road traffic injuries, low- and middle-income countries including Latin American countries are disproportionately affected. In Latin America and the Caribbean, the roadway fatality rate is approximately 17 fatalities per 100,000 inhabitants, compared to less than 10 fatalities per 100,000 inhabitants in high-income countries; this region has one of the highest road fatality rates in the world (Benitez and Unit, n.d.). From all the road users, VRUs that include mainly pedestrians and PTWs, represent almost half of the road fatalities in the Americas; 22% pedestrians and 20% PTWs of the fatalities; and worldwide; 22% pedestrians and 23% PTWs of the fatalities (World Health Organization, 2015) (Haworth, 2012). The risk of injury or death varies by road user types and pedestrians represent a high percentage of fatalities. In 2013, the percentages of pedestrians of road fatalities in Paraguay, Colombia and Chile were 25%, 29% and 39% respectively (International Transport Forum, 2017). Pedestrians are VRUs as they are susceptible to fatal injuries during collisions with motor vehicle. In Colombia, 23% of the pedestrian fatalities were in collisions with a car, 20% with a bus or truck and 33% with a PTW (International Transport Forum, 2017).

The increasing use of PTWs for passenger and goods transport in Latin American countries, accompanied with the lack of road safety programs has deteriorated the existing safety problem. In Bogota, for instance, the percentage of PTWs users in traffic fatalities increased from 18% in 2013 to 28% in 2017 (Secretaría Distrital de Movilidad de Bogotá, 2017a). Prior research has found that safety issues associated with PTWs are often linked to dangerous driver behavior such as speeding, red light violations, inappropriate passing maneuvers, sudden lane changes, and traveling in the wrong direction (Le et al., 2016). In particular, PTWs tendency to maneuver their way between other vehicles, and non-lane-based movements are main factors affecting crash risk of PTWs (Indriastuti and Sulistio, 2010). Despite all these countries requiring the use of a helmet, few of them have clear policies regarding its road safety. One exception is Bogota, where officials have established a road safety plan that defines 100 actions to address road safety risk of PTWs. The actions are divided into different categories: training, communication and education, the use of PTWs for work, control and surveillance, vehicle awareness, and infrastructure. The authorities additionally encourage drivers to take free training courses to protect their lives (Secretaría Distrital de Movilidad de Bogotá, 2017b).

While many developed countries have established road safety programs, action plans, and methods for their implementation (e.g. "vision zero"), such programs are often absent or weak in Latin America. Among many other factors, this can be attributed to the lack of economic resources, safety-related data and tools for safety analysis. Road traffic data and crash data frequently do not exist or are limited in quality in Latin American Countries (Ahmed et al., 2017). This is due to the absence of institutional arrangements and financing to develop and manage crash notification and registration systems. As a result, levels of underreporting can be as high as 50% (Ahmed et al., 2017). In LA, crash data suffers from inconsistencies, misclassification, inaccurate geographical locations and inaccurate identification of crash contributory factors (Imprialou and Quddus, 2017). In addition, it can take years to gather sufficient crash data for diagnosis and countermeasure evaluation, making it difficult to determine failure mechanisms that lead to crashes and contributing risk factors (Ceunynck, 2017; Jing, 2017; Lord and Miranda-Moreno, 2008). In this context, there is a need for data and methodologies for safety analysis that do not only rely on crashes but also that promote more proactive approaches to address the safety issue.

Instead of using crash reports and crash-based methods, surrogate measures of safety (SMS) offer an alternative approach. These measures include the analysis of road user interactions or conflicts that do not turn into crashes but can be observed frequently. SMS can be divided into measures of time or distance proximity, such as post-encroachment time (PET) or time-to-collision (TTC), and event severity such as speeds, trajectory angles, type of road users involved, etc. SMS could also include behavioral indicators such as violations or inappropriate driving behaviors with respect to the traffic rules (e.g. red violations, speeding, passing maneuvers) (Alhajyaseen, 2015; Guo et al., 2018; Johnsson et al., 2018). When examining the risk factors of VRUs, driver behavior is crucial. Proximity surrogate safety measures are not enough to measure conflict severity in less organized environments (Tageldin et al., 2017). These indicators cannot showcase the behavioral issue, where certain events can be used to try to quantify the PTWs risk like maneuvering behavior, right-of-way violations, and riding in the opposite direction (Chang et al., 2019).

Despite the increasing popularity of SMS and video analysis software, little research has taken advantage of the surrogate safety approach for studying VRUs safety and very little has been documented about the key factors contributing to road injuries and the mechanics leading to crashes in the LA context (Mahmud et al., 2017). Most of the safety studies use accident data from police reports to investigate the factors related to the occurrence and severity of crashes using statistical models (Chang et al., 2019; Indriastuti and Sulistio, 2010; Marizwan et al., 2012). SMS could help better understand the factors and behaviors that contribute to crash risk in LA cities and offer an alternative approach that can be low-cost and time efficient. SMS could help evaluate low-cost temporary countermeasures before the installation of permanent treatments and can provide a rapid analysis in the stages of diagnosis and in before-and-after studies, potentially taking days instead of years. Additionally, they can allow for the development and implementation of proactive road safety programs and strategies, enabling authorities to act before collisions occur.

The general objective of this thesis is to introduce the use of SMS and methodologies for VRUs in the context of LA using video analysis techniques. More specifically, the first half of this research (Chapter 3) has two objectives. The first objective is the adaptation and implementation of a surrogate safety methodology for pedestrian safety analysis using a video analytics tool. This includes the identification of risk contributing factors during vehicle-pedestrian interactions at three popular types of junctions. The second objective is the implementation of a surrogate before-after approach for evaluating low-cost countermeasures. For this research, a pilot project involving a small sample of intersections in the city of Cochabamba in central Bolivia is used as case study. Cochabamba is the fourth largest city in the country, with an urban population of more than six hundred thousand citizens and a large indigenous population. Urban mobility in the city is highly dependent on public transit and walking, given that a substantial portion of the population are low-income individuals. A total of 1,919,577 trips are made during a weekday, with 53% of those made by public transportation, and 24% by walking (ICES, 2013). In 2012, there were 4,116 crashes (22% of those crashes involved a pedestrian) in the metropolitan area of Cochabamba, representing 10% of those at the national level in the same year. The area also has one of the highest mortality rates for pedestrians in the country; for every five crashes that were fatal, two involved a pedestrian (Motorizado, 2015). This study involves the three main types of junctions: non-signalized and signalized intersections with three and four legs and roundabouts (including an old traffic circle). For the countermeasure evaluation, low-cost treatments are temporarily implemented at two intersections, using a similar approach to the one referred to as "tactical urbanism design".

The second half of this research (Chapter 4), aims to implement a video-based surrogate safety methodology to investigate PTW risk factors using various surrogate indicators such as speed, measures of proximity and behavior in urban environments. This study is carried on in two cities, Cochabamba in central Bolivia, and Bogota, Colombia. The first is selected because, although PTWs comprise a small but rising percentage of the total trips, prior research using SMS methods in the city has found that they significantly contribute to speeding and other risky behaviors (Scholl et al., 2019). The second city was selected because of its high percentage of PTWs in the modal distribution as well their significant and increasing contribution to road fatalities. Three types of analyses are conducted: a speed analysis using all road users, a conflicts analysis using 1200 conflicts all involving at least one PTW, and finally a behavioral analysis of a subset of those conflicts whose PET is less than 3 seconds using manual examination of the conflicts recorded videos.

Chapter 2 Literature Review

2.1 PEDESTRIANS SAFETY AT INTERSECTIONS

2.1.1 Pedestrian safety in the context of developing countries

Active transportation, typically in the form of walking, is an essential mode of transportation in Latin-American countries, in particular for low-income individuals. Walking is associated with many individual and public benefits, such as improved health and reduced traffic congestion, however, it is also perceived as a dangerous mode of transportation from the perspective of road safety (Nantulya, 2002). Pedestrians face a greater risk of injury and are involved in a disproportionate number of vehicle collisions in urban areas, leading them to be vulnerable road users. (Mohan, 2002).

Past research on pedestrian safety at crosswalks in developing countries (Ali and Najafi, 2013; Asaithambi et al., 2016; Ferenchak, 2016; Hamed, 2001; Quistberg et al., 2014) finds that in many south American cities, pedestrians are involved in a high proportion of vehicle conflicts. Given a lack of adequate pedestrian infrastructure, pedestrians often wait in the street instead of on the sidewalk before crossing, leading to increased exposure. Moreover, both vehicles and pedestrians frequently do not comply with traffic rules: vehicles fail to yield to pedestrians and pedestrians cross roads outside of crosswalk boundaries (Poó et al., 2018). Although the safety of pedestrians is a heavily researched topic in developing countries, limited work has examined vehicle-pedestrian interactions and conflicts, which can help in identifying the causes of collisions. Pedestrian safety studies have been conducted mainly using crash data, which as discussed before, can be problematic. Crash data suffers from several issues including underreporting, location errors, misclassification and long data acquisition time periods (Lord and Miranda-Moreno, 2008).

2.1.2 Surrogate safety and user preferences

Due to the limitations of using crash data, many studies have attempted to use, as an alternative approach, surrogate safety measures to investigate pedestrian-vehicle interactions and conflicts (Johnsson et al., 2018; Mahmud et al., 2017; Peesapati et al., 2013). Methods for surrogate safety can be categorized as either event-based techniques or as traffic flow techniques. Analyses that consider the occurrence or severity of individual "near-crash" events (including individual conflicts) are considered event-based techniques. Other surrogate safety techniques may use aggregate measures of traffic flow, including traffic volumes and speeds. Common event-based surrogate measures of safety include time-to-collision (TTC) and post-encroachment time (PET) as surrogates for the likelihood of collision. TTC is "the time required for two vehicles to collide if they continue at their present velocity and on the same path" (Van Der Horst et al., 2014) or, more generally, if their movements remain unchanged. However, this technique can be modified to include variations in speed and direction using motion prediction. TTC is measured continuously and, depending on the choice of motion prediction method, will yield a vector of measurements over time when there is a collision course. PET is the difference in time between the first and second road users arriving at the potential conflict point (Peesapati et al., 2013). PET is based on observed trajectories and can be computed only if trajectories intersect. Both PET and TTC can usually be computed for the same interaction and are complementary in the analysis of conflicts (Van Der Horst et al., 2014). PET is better suited for interactions involving turning movements than TTC (with the assumption of constant velocity). PET is also simpler and faster to compute than TTC (with more realistic motion prediction methods). For a literature review on the alternative surrogate safety measures proposed in the literature, one can refer to (Johnsson et al., 2018).

Conflicts between pedestrians and vehicles may be divided into discrete severity levels based on different PET and TTC thresholds. To measure conflicts based on PET or TTC, video-based devices, which provide rich positional data are common. Although rarely used in Latin American countries, the development of computer vision techniques has created the possibility of investigating conflicts and crossing behaviors in a more precise and microscopic way (Fu et al., 2018; Mahmud et al., 2017; St-aubin et al., 2016).

Research on user preferences and behavior can also help improve road safety in a proactive way. In Latin American countries, preferences of pedestrians are overlooked in most studies and engineering plans, as the focus is often on vehicles. (Ivan et al., 2001; Perdomo et al., 2014) used a stated preference survey to evaluate pedestrian preferences at roundabouts and to quantify how some roundabout features can be compensated for by other design features. The survey results show that pedestrians prefer roundabouts with pedestrian crossings, low traffic volumes and low vehicle speeds. An increase in the number of lanes has a negative impact on pedestrian safety perception. The authors found that perceived risk can be mitigated through design features; for example, to compensate for high traffic volumes, pedestrian islands can be installed.

2.1.3 Treatments and before-after studies for pedestrian crossings

In developed countries, before-after studies are often implemented to investigate the effectiveness of treatments applied to sites strategically selected using warrants or guidelines (AASHTO, 2010). Effectiveness is then evaluated by comparing the crash frequency and/or rates before and after the implementation of countermeasures. Alternative statistical approaches can be used for this purpose (Diogenes and Lindau, 2010; Ivan et al., 2001). In developed countries, a wide variety of countermeasures have been investigated to address pedestrian safety issues. The effectiveness of the measures depends on the road and traffic conditions and the compliance of the population with traffic rules, among other factors. Infrastructure measures such as installing traffic and pedestrian signals, extending curbs, building raised medians on multi-lane roads and improving lighting and visibility have been found to be effective to varying degrees (Mead et al., 2014). For instance, in a study conducted in Israel by (Gitelman et al., 2017), raised pedestrian crosswalks were installed at eight sites to replace non-signalized pedestrian crosswalks, building a speed hump in each travel direction, and traffic signs. The before and after the treatment behaviors of road users were compared, using video recordings and free-flow speed measurements, and a decrease in vehicle speeds when approaching the crosswalks and the rates of vehicles yielding to pedestrians increased, leading to an improvement in safety.

In Latin American countries, the investigation of treatment effectiveness is a less common practice. Among the few studies, (Diogenes and Lindau, 2010) used reported pedestrian crashes in Porto Alegre, Brazil, to evaluate the potential risk of pedestrian crashes at midblock crossings with and without traffic signals using a Poisson regression model. The authors found that pedestrian crash risk is influenced by the presence of busways and bus stops, road width, traffic volume and the number of lanes. Despite the large body of literature on pedestrian safety, there is a lack of research investigating pedestrian safety in the Latin American context. In part, as mentioned previously, this is due to the lack of crash data. Hence, methodologies for identifying risk factors and evaluating the effectiveness of countermeasures are lacking. Several before-after studies have been documented in developed countries using surrogate safety analysis, however, to the authors' knowledge; no studies have documented the feasibility of this approach in low-income countries. Moreover, in developing countries, there is a need to identify low-cost treatments so that they can be replicated in large numbers (at the city scale). To reduce costs and impacts of ineffective treatments, the evaluation of temporary design countermeasure is also recommended before the installation of permanent treatments. Therefore, the idea here is to be able to evaluate the impact of low-cost and temporary changes to the road environment in a short time period using a surrogate safety approach.

2.2 PTWS SAFETY AND RISK CONTRIBUTING FACTORS

This literature review is divided into four subsections. First, a review is provided regarding the PTWs risk and behavioral problems. In the second section, a review of the conflict between PTWs and other road users is detailed, including the maneuvering problem. A third section explores the use of PTWs for mobility and delivery, and the final fourth section summarizes some of the existing surrogate safety methodologies for PTWs.

2.2.1 PTWs risk and behavioral problems

Improved urban mobility provided by PTWs is accompanied by significant safety concerns due their high crash risk with respect to other transportation modes, which are likely to grow with increasing numbers of PTWs on the road. Several studies indicate that human error and behavioral issues to be the predominant causes of PTWs crashes (Ding et al., 2019; Hurt et al., 1981). PTWs riders account for 23% of total traffic fatalities (World Health Organization, 2015) and they are very susceptible to fatal injuries when involved in a serious collision (Haworth, 2012). As PTWs are more likely to speed and maneuver in traffic than other road users (Horswill and Helman, 2003), the relationship between PTWs risk and the riders' behavior needs to be analyzed. It was reported that in 50% of cases the cause of crash was human error by a car driver and in a further 37% of cases, the cause was human error by the PTW rider (MAIDS, 2004). There are multiple types of PTWs crashes that pose risks to riders. According to (Wu et al., 2018), the top five most frequent and severe types of crash sequences were identified to be (1) run-off-road crashes on the right, and hitting roadside objects, (2) cross-median crashes, and rollover, (3) left-turn oncoming crashes, and head-on, (4) crossing over (passing through) or turning into opposite direction at intersections, and (5) side-impacted. Also, other factors were identified to affect crash severity include helmet use, presence of horizontal curves, alcohol consumption, road surface condition, and night-time.

Speed analysis is essential to analyze PTWs crashes. There is a significant relationship between relative speed and injury severity in PTWs crashes, as demonstrated by (Ding et al., 2019). At 70 km/h, the risk for at least serious injuries in collisions with wide objects, crash barriers and narrow objects was 20%, 51%, and 64%, respectively and head-on collisions between PTWs and passenger cars, with both vehicles traveling at 60 km/h (a relative speed at 120 km/h), present 55% risk of at least serious injury to the PTW rider (Ding et al., 2019).

The severity of PTWs risk increases with the increase of number of PTWs in the streets. In the city of Danang in Vietnam, PTWs constitute over 80% of total traffic and PTWs crashes account for nearly 70% of the total road crashes (Danang Department of Transportation, 2013). In Indonesia, the number of PTWs reached 78.3% of the total vehicle population and 75% fatalities of traffic crashes involved motorcyclists (Amelia and Harnen, 2010). In PTW-dominated traffic conditions, changing lanes improperly and failing to keep safe following gap are two major causes of PTWs crashes (Danang Department of Transportation, 2013). Risk factors such as front distance, longitudinal gap, lateral gap, lateral clearance, speed difference, and operating speed also have a significant contribution to PTWs crash risk (Le et al., 2016).

2.2.2 PTWs conflicts and maneuvering issue

PTWs have distinguishable characteristics as they are capable of maneuvering between other vehicles and, on average, have higher speed which increases the number of serious conflicts they are involved in and causes them to have a significant effect on the traffic conditions. PTWs may reduce the speed of the other modes of transportation and may lead to further congestion because of their shape, small size, and maneuverability (Minh et al., 2012). As PTWs maneuver their way to the front of the queue in traffic, they can obstruct and slow down the speed of surrounding vehicles.

Also, according to (Minh et al., 2012), PTWs conflicts become more serious at signalized intersections as they do not follow the ‘‘First In First Out’’ rule like other vehicles do and they try to creep to the front of the queue during queue formation or queue discharge for various reasons like attempting to stop at a favorable position during queue formation, avoiding traveling behind a heavy vehicle, preparing for making a turn or avoiding an obstruction.

The lateral distance between two-wheelers and vehicles is an important indicator for risk severity. (Guo et al., 2019) found that the average lateral distance, which is the distance the two-wheeler chooses to keep from the vehicles, between overtaking two-wheelers and vehicles is 1.54m and that the type of two-wheeler, evasive action manner, yaw rate ratio, the presence of heavy vehicles and the speed difference between the two-wheelers and the conflicting vehicles are related to the probability of the two-wheeler abiding to the critical lateral distance.

The commonly used time proximity surrogate safety measures, time to collision TTC and post encroachment time PET, may not be effective for evaluating PTWs safety or measuring conflict severity in less organized traffic environments. A study by (Guo et al., 2018) analyzes the effectiveness of TTC vs evasive action-based indicators, e.g. yaw rate and jerk, for evaluating the severity of PTW conflicts. It was found out that yaw rate is good for identifying conflict severity for PTWs while TTC isn't which highlights the importance of choosing the correct indicators to analyze conflicts in chaotic environments, especially when separation between humans and vehicles is not clear.

2.2.3 PTWs for mobility and delivery

There is a growing use of PTWs not only for passenger transportation but also for delivery in many developing countries, due to obvious reasons that include their high mobility, their speed and low cost of ownership and operation. In Seoul, South Korea, more than 56% of PTWs are used for food and parcels delivery. Traffic violations usually occur as fast delivery time is required from the delivery PTWs. These violations include, but are not limited to, crossing the centerline, speeding over the speed limit, crossing while the light is red, and driving in the opposite direction. Although PTWs crashes account for only 5% of road crashes in South Korea, the fatality rate for PTWs is 12% of the road crashes fatalities, which is quite high (Chung et al., 2014).

The same problem is easily observed in Latin American countries, for example in Bogota, Colombia, where a significant increase in the number of PTWs in the streets can be observed in the recent years as the percentage of PTWs of the total vehicles increased from 29.1% in 2003 to 49.6% in 2012 (Jimenez et al., 2015; Registro Único Nacional de Tránsito de Colombia, 2013). A survey conducted by "CAF – Development Bank of Latin America" in five Latin American cities showed that 37% of PTWs users own a PTW for work, 32% identified as PTW taxi passengers, and 31% own PTWs for private use. From the 37% using them for work, 58% used it as a PTW taxi, 18% for delivery and 24% as a courier and for other uses (CAF – Development Bank of Latin America, 2015). Delivery companies like "Rappi" are expanding their reach and while providing people with the convenience or ordering almost anything online, there are severe safety implications accompanied with the increase of delivery PTWs in the crowded city's streets. New policies and laws, that focus on the behavioral aspect of PTWs, are required to reduce the number of crashes and the injury severity between PTWs and other vehicles.

2.2.4 Safety research methodologies for PTWs and literature gaps

Various studies on PTWs safety have been documented in the last few years and most of them have focused on the identification of factors related to the probability and severity of observed crashes using accident databases from low and middle-income countries. (Marizwan et al., 2012) analyzed the frequency of PTWs crashes at urban junctions in Malaysia using generalized linear models and four-year PTWs accident data and found out that the approach speed of vehicles, junction geometry and junction control are among the factors contributing to PTWs crashes. Amelia and Harnen (2010) built a probability model to predict PTWs crashes in Indonesia and they suggested that gender, the increase of PTWs ownership, long travel distances and little riding knowledge are factors that have a significant impact on the occurrence of PTWs crashes. (Chang et al., 2019) uses a police-reported crash database to investigate the relationship between irregular driver behavior and injuries in PTWs. They use multilevel mixed-effects ordered logit models and found that driver behavior of violating others' right-of-way, riding in the opposite direction, and not obeying traffic control devices are factors contributing to the increase in risk. (Njå and Nesvåg, 2007) analyzes accidents involving adolescent light PTW riders, namely moped and light motorcycles, based on their driving behavior and socio-cultural perspective. The data is gathered by conducting interviews based on previous traffic accidents and the results showed there is a connection between social mechanisms and how PTWs behave in traffic. (Guo et al., 2018) uses video data, automated computer vision and regression models to evaluate the effectiveness of evasive action-based (yaw rate and jerk) indicators for checking the severity of PTWs conflicts and found out that different conflict indicators are suitable for evaluating conflict severity of different types of PTWs. (Minh et al., 2012) mention that to model the PTWs behavior, one needs to consider their lane-changing and maneuvering behavior, thus maneuverability models for PTWs in queues at signalized intersections, that use microscopic data collected from video images, are proposed. Most of the previous studies used historical crash data, making them susceptible to the poor traffic data quality in low- and middle-income countries. Very little has been documented about the dangerous maneuvering behaviors of PTWs and the relationship with speed, type of motorcycle, type of maneuver, usage of helmet, etc.

Surrogate safety measures offer an alternative approach to the traditional crash-based methods that can be cheaper and faster to apply allowing us to conduct studies in days, instead of years. Few studies using surrogate safety measures in developing countries exist. One such study examines the contributing factors to high risk traffic conflicts between vehicles and pedestrians in Cochabamba, Bolivia using data on vehicle-pedestrian interactions generated by machine learning algorithms applied to video recordings at a sample of intersections (Scholl et al., 2019). Applying a multilevel mixed-effects linear regression model, they find PTWs to be the single most important predictor of high-risk vehicle-pedestrian conflicts (as measured by speed and post encroachment time (PET)) relative to other modes. More studies are needed focusing on PTWs drivers' behavior and models focusing on traffic environments where the PTWs are the predominant road users, like in Bogota and some other Latin American cities.

Chapter 3 Pedestrian road safety diagnosis and evaluation of low-cost temporary countermeasures: Case study in Cochabamba, Bolivia

3.1 METHODOLOGY

The proposed methodology consists of the following steps:

1) identification and selection of sites, 2) video data collection and processing, 3) generation of surrogate safety measures, 4) cross-sectional analysis for identifying contributing factors using regression techniques, and 5) implementation of low-cost countermeasures and effectiveness evaluation

3.1.1 Identification and selection of sites

The selection of sites (intersections) was carried out through the participation of a local working group of the city of Cochabamba that included transportation engineers and planners working for the local government and road safety experts from the Inter-American development Bank. A preliminary large set of locations was first defined by the local authorities. After a field visit, a final short list of sites was selected for the diagnosis. The site selection was done in such a way that the three most common types of intersection crossings in the city were included, which are pedestrian crossings at a T intersection, at 4-leg non-signalized and signalized intersections, and at roundabouts as shown in Figure 1. In order to observe the maximum number of interactions and have a wide range of traffic conditions, presence of high pedestrian activity and high vehicle traffic was considered in the site selection.

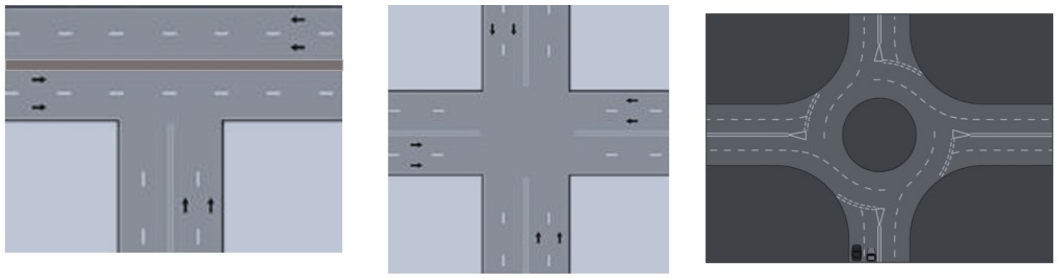


Figure 1: Types of intercessions considered in the study

3.1.2 Video data collection and processing

Data was collected using video cameras that were temporarily installed on existing infrastructure (lamp posts and buildings). High-definition cameras were used with a 2048×1536 resolution and 30 fps. Cameras were installed at a minimum height of five meters.

Collected video data was then processed using a computer vision software solution, *Brisk Lumina*, developed by Brisk Synergies (https://brisksynergies.com/), which integrates and utilizes deep and machine learning algorithms for traffic safety analysis. Video processing was conducted in three steps: 1) definition of scenarios of interest, 2) video calibration, and 3) data generation. Figures 2 and 3 show examples of traffic scenarios. A traffic scenario is composed of a vehicular traffic movement that interacts with pedestrians and generates crash risk exposure, such as through or turning vehicles interacting with pedestrians crossing at a given intersection approach. In roundabouts, movements are divided into a pedestrian interacting with vehicles going through the roundabout or turning to leave it.

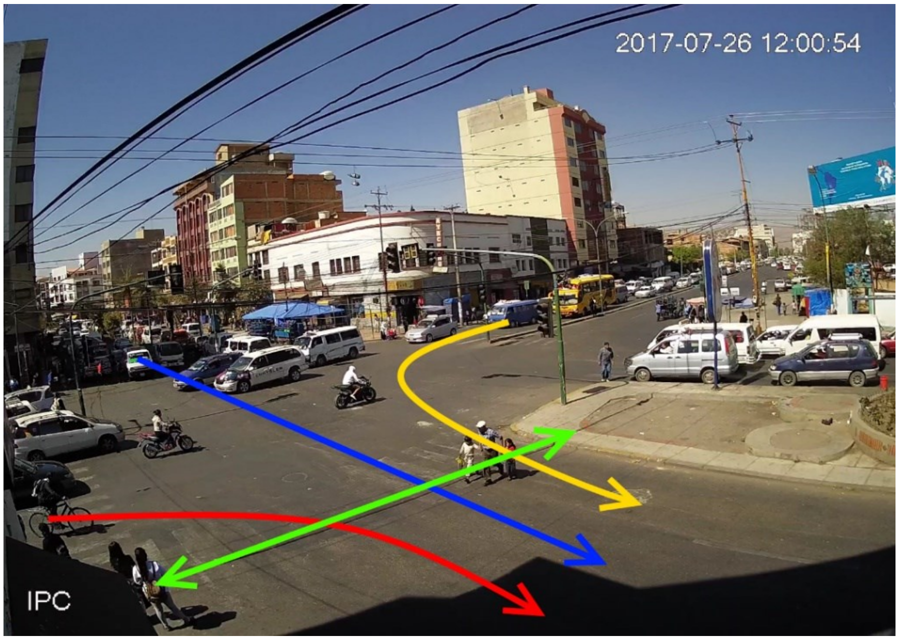


Figure 2: Vehicle-pedestrian scenarios at intersections

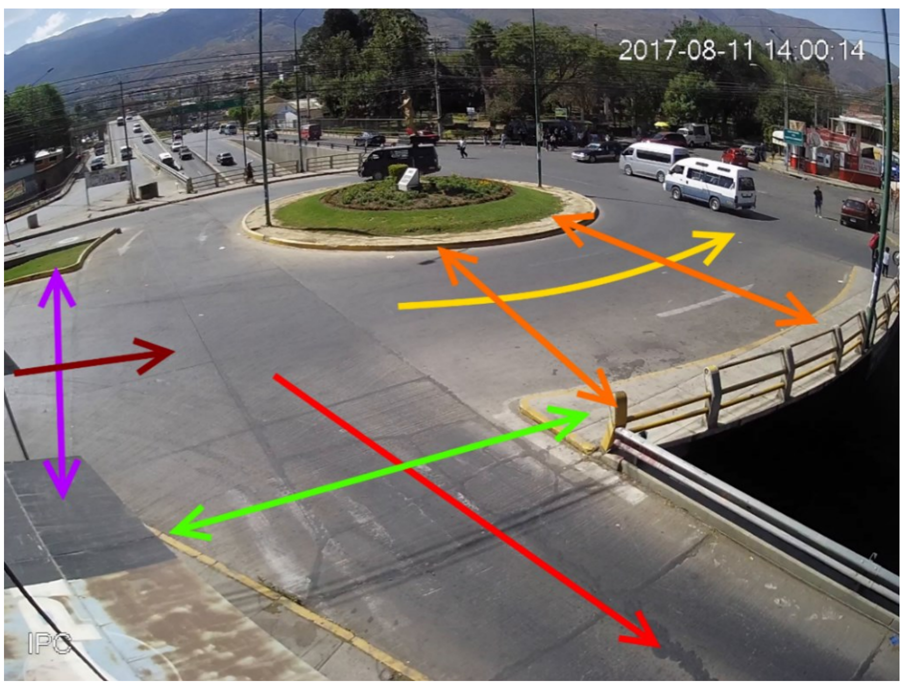


Figure 3: Vehicle-pedestrian scenarios at roundabouts

Video calibration included adjusting homography, defining the conflict zones, and applying pre-trained deep learning models. Homography is defined as two images of the same planar surface in space that are related to each other. In this case, the homography was used to map the points in the video corresponding to coordinates in the street. From the video footage, road users were then detected, classified, and tracked in the video, and data on road-user trajectories (position and speed at each frame), and speed, such as the median and 85th percentile of all instantaneous speeds, for each individual trajectory, were computed for each road user.

The commercial computer vision software was used for object (road-user) detection, classification and tracking. The object detection and classification elements utilized a deep learning neural network capable of detecting different types of objects (e.g. car, truck, bus, PTW, pedestrian, etc.). For improving detection and classification accuracy, the neural-network models had been trained on many large-scale datasets. Object tracking, road user trajectories were used to compute speeds and to calculate surrogate safety measures for each road user interactions (Figure 4).

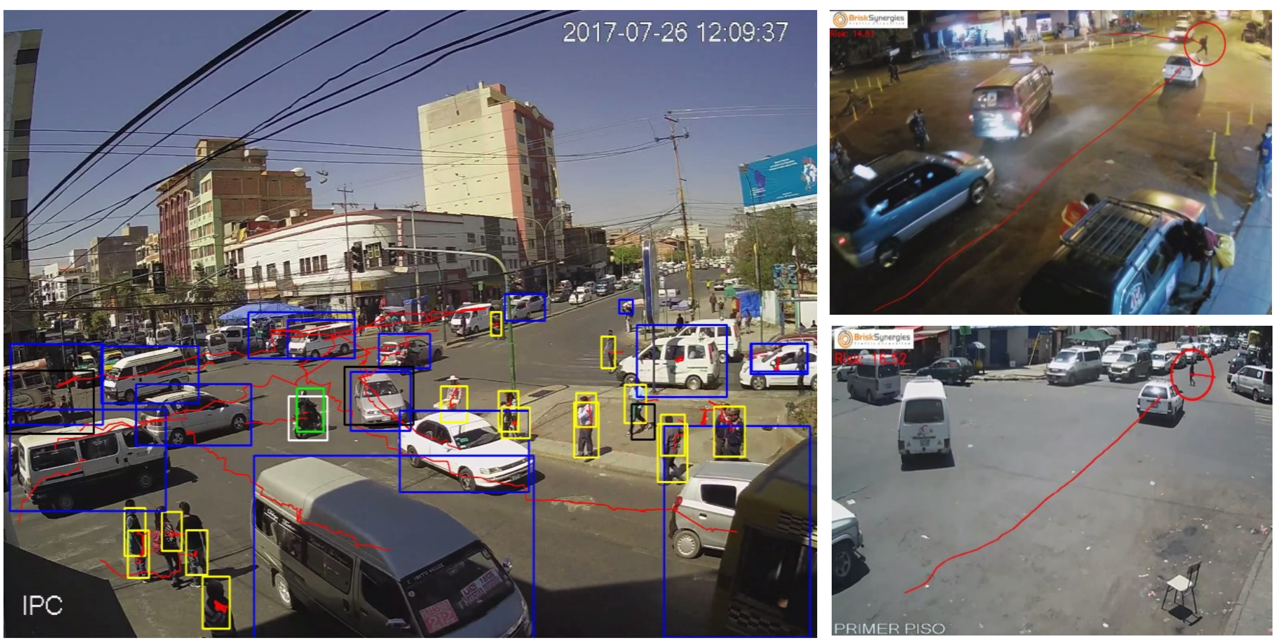


Figure 4: Example of Computer Object Classification & Conflict Detection

3.1.3 Generation of Surrogate Safety Measures

PET and speed measurements were selected as the surrogate safety measure in this research as all the vehicle-pedestrian interactions involve intersecting trajectories. PET measurements are defined as the time between the moment that the first road-user leaves the common conflicting area (t1) and the time that the second reaches the same area (t2), thus PET = t2 - t1 as illustrated in Figure 5. The lower the PET, the closer the conflict was to resulting in a collision.

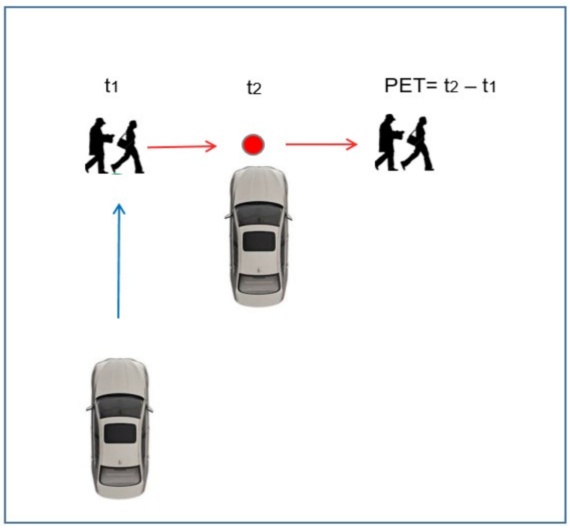


Figure 5: Illustration of post encroachment time (PET)

To characterize each event according to its severity, speed measures, such as the median and 85th percentile of all instantaneous speeds observed for each individual trajectory, were computed for each road user. These speed measures are used as a surrogate indicator of the crash risk potential associated with the vehicle-pedestrian interaction (Ceunynck, 2017). As recognized in the literature, vehicle speed is a key predictor of pedestrian injury likelihood in the case of a pedestrian-vehicle collision. Therefore, as PET alone is insufficient to estimate the relative risk of a given interaction, we classify interactions into different risk levels based on the PET and the 85^{th} percentile speed of each vehicle. We combine the PET and VS_{85} into a single indicator, a risk index

(RI) is defined as RI = VS_{85}/PET. In addition, risk level of a given interaction is a function of several environmental and contextual factors presented in table 1.

Table 1: Definition of variables

Variable	Description	Categories / Units
PET	Post-Encroachment Time between two road users	Seconds
VS_{85}	85^{TH} percentile of the vehicle speeds	km/h
Risk index	This is the ratio of VS_{85} and PET	VS_{85}/PET
Intersection type	Intersection type where study crossing is located	Categorical variable with 3 categories: 3-leg, 4-leg or roundabout
Arrive first	Who arrives first to conflict point: the pedestrian or vehicle	0 = vehicle and 1 = pedestrian
Movement type	Type of vehicle movement when traversing intersection	Categorical variable with 3 categories: right, left or through movement interactions
Peak hour	The interaction is during peak hours (7 am to 9 am, 3 pm to 5 pm).	0 = not peak hours and 1 = peak hours
Night-time	The interaction is during night-time (7 pm to 7 am).	0 = daytime and 1 = night-time
Crossing distance	Crossing distance that the pedestrians must walk.	Meters
Traffic flow	15-min vehicles traffic count at crossing point	Vehicles per 15min
Vehicle type	The type of vehicle involved in the interaction.	Categorical variable with 4 categories: car, truck, bus or PTW
Treated	Whether the interaction has been treated site or not.	0 = not treated (before) and 1 = treated (after)

According to (European traffic Safety Council, 1995), the probability of a fatal pedestrians injury involving a vehicle at 32 km/h, 48 km/h and 64 km/h car speeds, is 5%, 45% and 85%, respectively.

The human reaction and braking time depends on the driver's age, physical condition and concentration, but 1.5 seconds can be considered the average estimate for the simplest kind of reaction time to react to a potential collision (Koppa, 1975). (National Safety Council, 2005) recommends 3 seconds minimum spacing for reaction time between vehicles traveling in the same lane. Thus, wee classify risk into three categories, low, moderate, and high, based on collision probability (PET) and severity of injuries (vehicle velocity) at impact. Figure 6 shows the conflict severity by PET and speed where the speed represents the 85th percentile speed of the involved vehicle in km/h, and the PET is in seconds. Red represents high-risk conflicts where speed is higher than 48 km/h and PET is lower than 1.5 seconds, yellow represents moderate-risk conflicts where speed is higher than 32 km/h and PET is lower than 3 seconds, cyan represent low-risk conflicts and green represents safe interactions. The thresholds for each category are shown in figure 6.

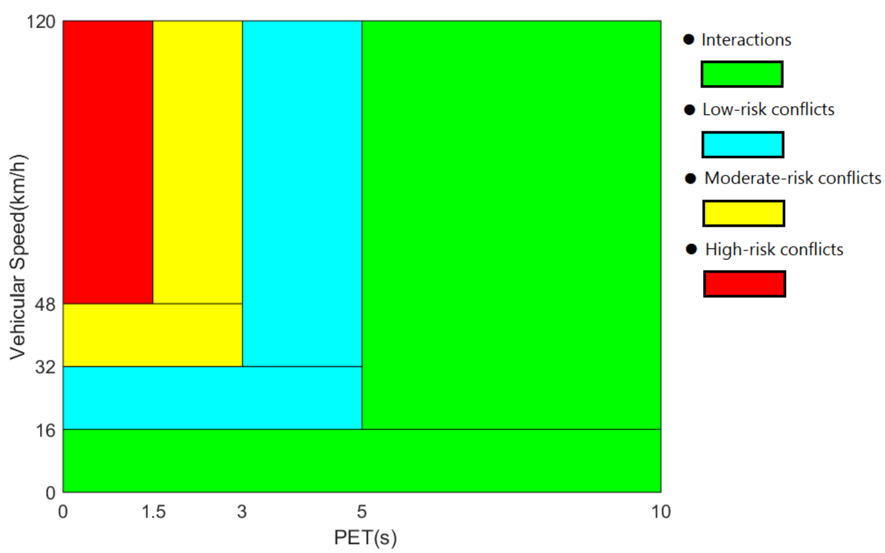


Figure 6: Conflict severity classification

3.1.4 Cross-sectional statistical analysis

To identify salient factors associated with vehicle-pedestrian conflicts, a regression analysis with intersection fixed and random effects for the three surrogate risk indicators was carried out, with each event as the unit of analysis. For each interaction with PET < 10 seconds, the 3 indicators are: 1) the log of the risk index, the inverse of PET (1/PET) and vehicle speed. Random and fixed effect models were attempted to identify the relationship between these outcomes:

$$y_{ij} = \beta_0 + \beta_1\, x_{i\,1} + \beta_2\, x_{i2} + \cdots + \beta_p\, x_{ip} + \alpha_j + \varepsilon_{ij}\ (1),$$

, i=1, 2,…..,n

Where:

y_{ij}- represents a surrogate risk measure such as the ln (RI=V/PET), 1/PET, and V derived for each vehicle-pedestrian interaction i occurring at site j.

x_i - the vector of explanatory variables (in this case, night time, peak hour, intersection type, movement type, etc.). In the case of the before-after study, a dummy variable is introduced to the model for evaluating the treatment effect of the surrogate safety outcomes.

α_j –fixed effects errors for each site j

β_p – is the vector of unknown regression parameters

ε_{ij} – represents the random error of the regression estimate

We evaluated a large set of models, combining type of intersections, which user type arrived at the collision point first and the three risk indicators. We calculated PET and other risk measures for all vehicle-pedestrian interactions in which the pedestrian arrives first to the conflicting area, those events that represent a greater risk for pedestrians. Conflicts where the pedestrian arrives second are considered as events more likely to be related to yielding behavior issues, which are beyond the scope of this research. As the value of PET decreases, the probability of collision increases; thus, higher values of 1/PET, speed, and speed/PET, are not desirable from a traffic safety point of view. In the modeling results, positive coefficients correspond to more dangerous scenarios and negative coefficients correspond to safer scenarios.

3.1.5 Temporary treatment design and implementation

To illustrate the methodology in the context of before-after studies and to investigate the potential impact of low-cost temporary countermeasures to protect pedestrians, two locations were selected for the implementation of designed countermeasures. A 4-leg intersection, site ID 4, with two lanes in each direction, and a large roundabout (an old traffic circle), site ID 5, with eight points of entry and exits.

Both sites lacked lane and crosswalk pavement marking. Also, vehicle turning radius and crossing distances were very large in particular for the old-traffic circle. Accordingly, curb extensions were implemented on the 4-legged intersection as a traffic calming measure to extend the sidewalk, reducing the crossing distance, reducing speeds and eliminating parking from the crosswalk area. The temporary design was implemented using temporal plastic bollards. The treatments reduced the pedestrian exposed crossing distance, from 13 meters to 8 meters. For the traffic circle, to reduce crossing distance, the median was extended also with bollards. In both locations, pedestrian crosswalk crossings were implemented using the standard white color with zebra patterns and with a width of 2.5m.

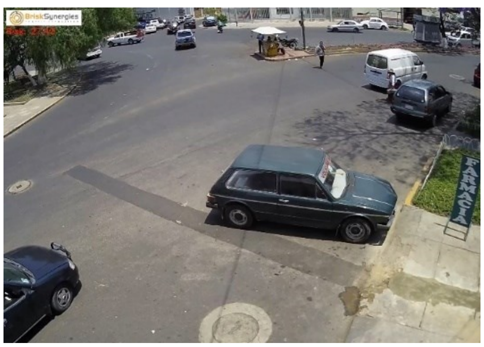
Table 2 illustrates the conditions before and after treatment implementation as well as the design concept. Video data was collected from the two sites before and after the treatment. Video recordings were conducted during the same hours and days of the week before and after the interventions. Note that the post-treatment (after) recordings took place within days of completing the road treatments.

Table 2: Treated 4-leg intersection and traffic circle: before and after temporary treatment implementation

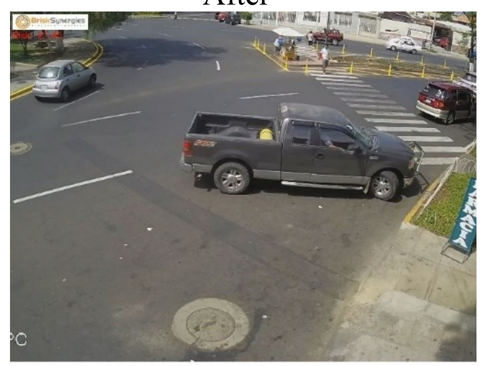

Before


Design concept*


After


Before


Design concept**


After

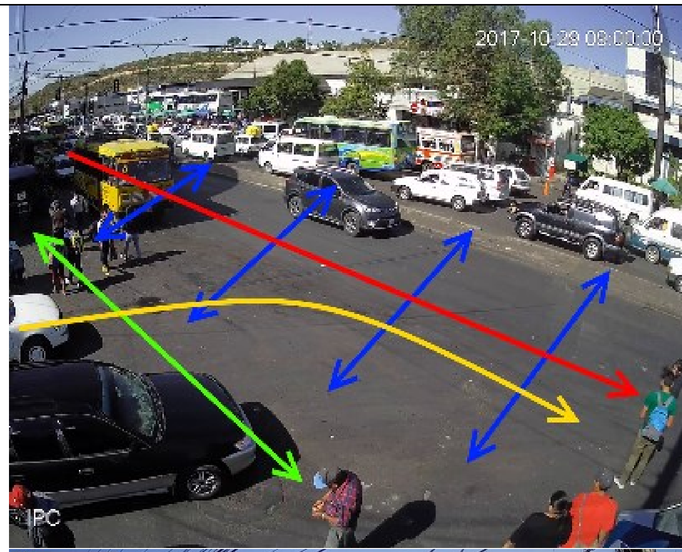
* Temporary treatments: crosswalk crossing and lane pavement marking along with curb extensions using flexible plastic bollards

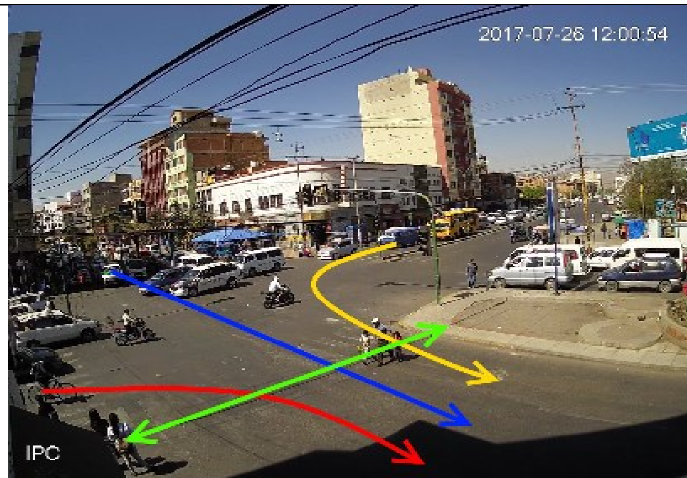
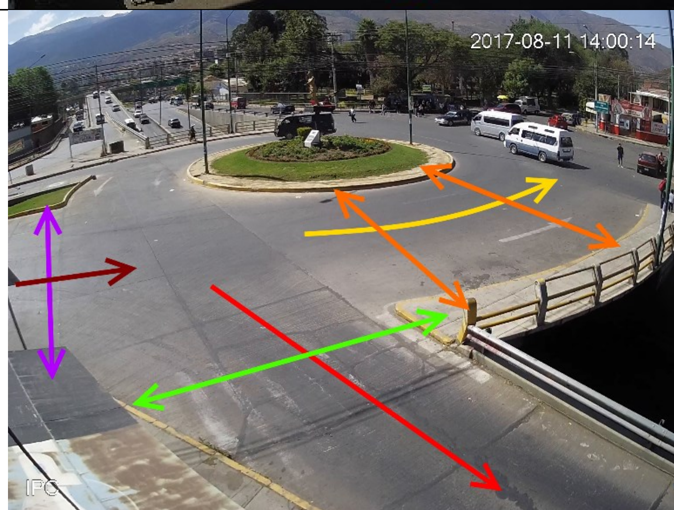
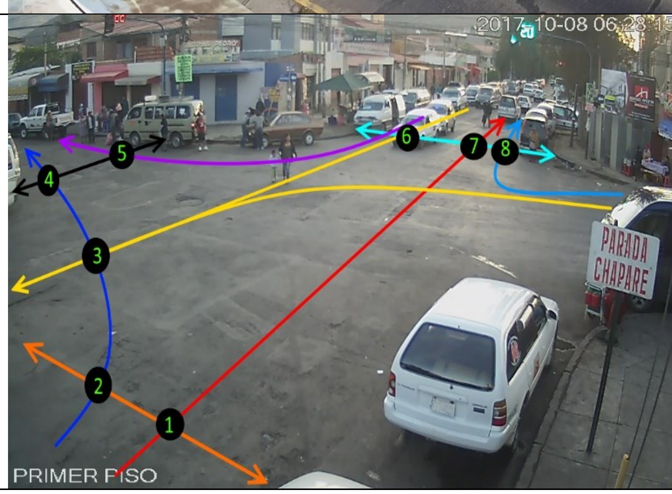
** Temporary treatments: crosswalk crossing and lane pavement marking along with the increase of the median width using flexible plastic bollards

3.2 DATA GENERATION

Table 3 shows a list of the sites analyzed in this study and Table 4 shows the number of observations per intersection and per site type.

Table 3: Study intersection, scenarios, and video hours

Type of intersection/name	Illustrative scenarios	Scenarios description
Intersection 1: 3-legged non-signalized intersection crossing Av. Ayacucho and Av. Punata	 	Blue and Green: Pedestrians Red and Yellow: Vehicles

Intersection 2: 4-legged signalized intersection crossing Av. Ayacucho and Av. Aroma		Green: Pedestrians Red, Blue and Yellow: Vehicles
Intersection 3: Roundabout crossing Av. Ruben Dario - Jardin Botanico		Purple, Orange and Green: Pedestrians Brown, Red and Yellow: Vehicles
Intersection 4: 4-legged signalized intersection crossing Av. Oquendo and Av. Republica		Black, Cyan and Orange: Pedestrians Blue, Red, Yellow, Purple, Light Blue: Vehicles

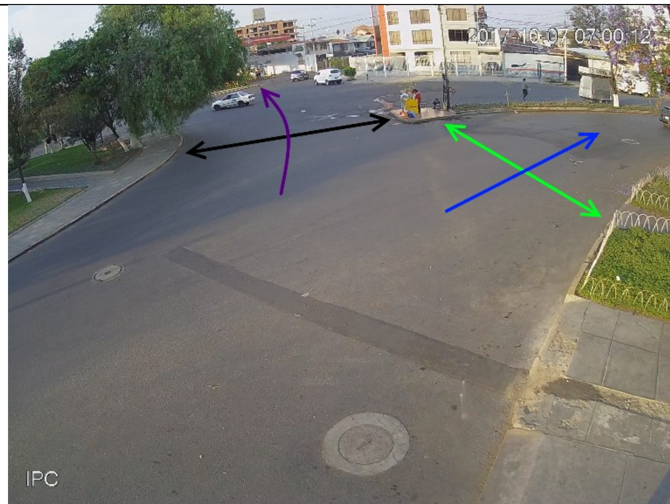
Intersection 5: Roundabout crossing Rotunda de Juan Pablo de la Rosa		First Picture: Black and Green: Pedestrians Purple and Blue: Vehicles Second Picture: Green: Pedestrians Red: Vehicles Third Picture: Red: Pedestrians Blue: Vehicles

Table 4: Observations per intersection and site type (only before)

	Type	Number of Observations
Study locations	ID 1 Av. Ayacucho and Av. Punata	6,470
	ID 2 Av. Ayacucho and Av. Aroma	12,955
	ID 3 Av. Ruben Dario - Jardin Botanico	323
	ID 4 Av. Oquendo and Av. Republica	3,534
	ID 5 Rotunda de Juan Pablo de la Rosa	933
	Total	24,215
Intersection type	3-leg or 4-leg Intersection	22,959
	Roundabout	1,256
	Total	24,215
Type of control	Non-Signalized	6,470
	Signalized	16,489
	Total	22,959

A summary of the surrogate outcomes for each of the sites is presented in Tables 5 and 6. For each PET less than 10 seconds, a set of variables was generated automatically for each road user trajectory and vehicle-pedestrian interaction. This includes 85th percentile, median, & 15th percentile speeds, vehicle traffic movements (right turn, left turn or through vehicle movement for intersections, and through or turning movement for roundabouts), who arrives first at the collision point, and whether the event occurred at night time or at peak hours. From the five study locations, thousands of vehicle-pedestrian interactions were recorded and detected automatically; from which trajectories, speeds and PET values were extracted. A summary is presented for intersection types: 1) standard intersections, with and without traffic controls, and 2) roundabouts. In addition to the intersection features, the vehicle movement was also identified in each vehicle-pedestrian interaction. Vehicle trajectories were classified accordingly as either through or turning movements (left or right). Surrogate risk measures vary substantially by intersection. Overall mean RI is 6.45km/h-s. For standard intersections, the average RI is 6.25 km /h-s, while for roundabouts it is higher, 10.07km/h-s on average. Vehicle speed in roundabouts are also substantially higher, 35.1km/h on average, versus 25.2 km/h for intersections, and 25.7 km/h overall. Peak hour observations represent 22% of the sample, while night-time events represent 27%.

Table 5: Summary statistics for all sites

ALL (INTERSECTIONS AND ROUNDABOUTS)					
Variable	Obs.	Mean	Std. Dev.	Min	Max
PET (seconds)	24,215	5.06	2.20	0.03	9.97
1/PET (1/seconds)	24,215	0.25	0.28	0.10	33.33
Speed (Km/h)	24,215	25.72	13.59	0.40	119.61
Night Time	24,215	0.27	0.44	0.00	1.00
Peak Hour	24,215	0.22	0.41	0.00	1.00
Crossing Distance	24,215	11.23	1.49	4.7	14
Traffic Volume	24,215	72.30	48.60	2	367
Vehicle Type	24,215	1.18	0.48	1	4
Ln (Risk)	24,215	1.62	0.67	-2.14	6.94
Risk (RI)	24,215	6.45	8.55	0.12	1028.67

Table 6: Summary statistics intersections vs roundabouts

	INTERSECTIONS ONLY					ROUNDABOUTS ONLY				
Variable	Obs.	Mean	Std. Dev.	Min	Max	Obs.	Mean	Std. Dev.	Min	Max
PET (seconds)	22,959	5.10	2.22	0.03	9.97	1,256	4.24	1.62	0.65	9.50
1/PET (1/seconds)	22,959	0.25	0.29	0.10	33.33	1,256	0.28	0.14	0.11	1.54
Speed (Km/h)	22,959	25.20	12.92	0.40	119.61	1,256	35.10	20.43	2.05	118.30
Night Time	22,959	0.27	0.44	0.00	1.00	1,256	0.17	0.38	0.00	1.00
Peak Hour	22,959	0.22	0.41	0.00	1.00	1,256	0.25	0.43	0.00	1.00
Crossing Distance	22,959	11.36	1.31	8	14	1,256	8.91	2.33	4.7	13.5
Traffic Volume	22,959	68.22	43.17	2	182	1,256	146.90	74.90	13	367
Vehicle Type	22,959	1.18	0.46	1	4	1,256	1.21	0.66	1	4
Ln (Risk)	22,959	1.60	0.66	-2.14	6.94	1,256	2.04	0.73	-0.83	4.54
Risk (RI)	22,959	6.25	8.51	0.12	1028.67	1,256	10.07	8.55	0.44	93.37

3.3 ANALYSIS AND RESULTS

This section is divided into two subsections. The first one presents the results of cross-sectional regression analysis and the second the results of a before-after study. Tables 7,8,10 and 11 present the coefficients of multilevel mixed effects regressions for the independent variables denoted in each row for the outcomes denoted in each column, using video-generated data conflicts between pedestrian and vehicles in the studied intersections. Statistical significance is indicated as follows: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. Standard errors are reported in parentheses

3.3.1 Cross-sectional regression analysis

The results of the regression analysis are presented in Tables 7 and 8.

Table 7: General Models

	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se
Night-time[1]	-0.024**	-0.005	0.034
	(0.010)	(0.004)	(0.188)
Peak-hour	0.039***	0.004	0.611***
	(0.011)	(0.005)	(0.199)
Traffic Volume	0.000	-0.000***	0.041***
	(0.000)	(0.000)	(0.003)
Bus	-0.156***	-0.011**	-3.337***
	(0.013)	(0.005)	(0.238)
Truck	-0.010	0.009	-1.321**
	(0.032)	(0.014)	(0.590)
PTW	0.599***	0.238***	15.182***
	(0.050)	(0.021)	(0.937)
Crossing Distance	-0.014***	0.002	0.035
	(0.004)	(0.002)	(0.079)
Turning Movement	0.113***	0.028***	-0.414

[1] Night time is from 7 pm to 7 am, and Peak hours are from 7 am to 9 am, 3 pm to 5 pm

	(0.015)	(0.006)	(0.281)
Roundabout	-0.460***	0.041*	-16.067***
	(0.175)	(0.024)	(5.693)
Turning Movement # Roundabout	0.813***	-0.001	22.946***
	(0.051)	(0.022)	(0.951)
Constant	1.688***	0.248***	22.079***
	(0.116)	(0.021)	(3.661)
Observations	24215	24215	24215

The results for the general model (which includes all intersection types) are presented in Table 7. Vehicle-pedestrian interactions occurring during night time are associated with reduced risk. During peak hours, events are associated with increased risk: RI increases by 3.9%, while vehicle speeds increase by 0.6 km/hr, relative to off peak. The pedestrians crossing distance has a small but significant effect on pedestrian risk. The risk index decreases by approximately 1.4% with each meter of width. However, the effect of crossing width on velocity and PET are statistically insignificant. The type of intersection also has an impact on pedestrian risk; the RI at roundabouts is 35% higher than the average RI. The most dangerous site was ID 5, the old traffic circle. That type of roundabouts, which is not uncommon in Cochabamba, poses a severe safety problem to pedestrians due to high vehicle speeds. Turning movements in roundabouts are particularly dangerous. Turning vehicles increase the conflict risk index by 11.3% overall but by 81.3% in roundabouts. This increased risk is related to vehicle speeds, as summarized in the tables. Vehicle speeds increase by 22.95 km/h for turning movements in a roundabout, (compared to a mean of 35.10 km/h for roundabouts). Traffic volume has a significant effect on speed; as traffic volume increases, speed increases. Vehicle type also impacts risk. Four types of vehicles are observed: cars, buses, trucks and PTWs. The cars are used as the comparative group, and it is observed that buses and trucks have lower speeds than cars. However, PTW speeds are, on average, 15.2 km/h faster than cars.

Table 8: Intersections and roundabouts only models

	Intersections only models			Roundabouts only models		
	Ln(risk)	1/PET	85th Percentile Speed	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se	b/se	b/se	b/se
Night-time	-0.023**	-0.005	0.078	-0.056	-0.010	-0.609
	(0.010)	(0.004)	(0.183)	(0.046)	(0.010)	(1.230)
Peak-hour	0.040***	0.004	0.570***	0.087**	0.012	2.157**
	(0.011)	(0.005)	(0.197)	(0.040)	(0.009)	(1.086)
Traffic Volume	-0.001***	-0.001***	0.016***	0.002***	0.000**	0.067***
	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.007)
Bus	-0.164***	-0.012**	-3.456***	-0.172**	0.017	-4.133*
	(0.013)	(0.006)	(0.231)	(0.087)	(0.020)	(2.336)
Truck	-0.058*	0.010	-2.926***	0.100	-0.008	6.421**
	(0.033)	(0.015)	(0.596)	(0.092)	(0.021)	(2.494)
PTW	0.609***	0.290***	15.245***	0.358***	0.059***	11.096***
	(0.057)	(0.025)	(1.032)	(0.093)	(0.021)	(2.499)
Crossing distance	-0.031***	0.000	-0.577***			
	(0.004)	(0.002)	(0.080)			
Signalized Intersection	-0.132**	0.021	-8.090***			
	(0.064)	(0.018)	(1.984)			
Right Turn	-0.117***	0.021***	-5.437***			
	(0.018)	(0.008)	(0.328)			
Left Turn	0.165***	0.016**	1.580***			
	(0.016)	(0.007)	(0.288)			
Turning Movement				0.882***	0.022**	22.039***

				(0.044)	(0.010)	(1.191)
Constant	2.099***	0.268***	36.716***	0.918***	0.241***	2.946
	(0.069)	(0.025)	(1.810)	(0.137)	(0.012)	(5.048)
Observations	22959	22959	22959	1256	1256	1256

Examining the intersections only (or non-roundabout) models in Table 8, left turn movements are the most dangerous for pedestrians, increasing risk by 16.5%, followed by through movements, and right turn movements are the safest. There are two types of intersections, signalized and non-signalized. Signalized intersections have lower PET values and lower speed, leading to a lower risk ratio (RI is 13.2% lower) indicating increased safety. Speeds increase significantly in intersections during peak hours (by 0.6 km/h) and risk increases by 4%. As in the general model, higher traffic volume is associated with higher the speed, and PTWs are the most dangerous vehicle type for pedestrians.

In the roundabout only models in Table 8, night time has an insignificant effect on risk. In contrast, peak hours lead to an increase in risk by 8.7% and an increase in speed by 2.2 km/h. Turning movements have higher speed & risk than through movements. It was observed that site 5 (Rotunda de Juan Pablo de la Rosa), which is the bigger of the two roundabouts, poses more risk than site 3 (Av. Ruben Dario - Jardin Botanico), the smaller roundabout. Consistent with the findings for the interaction terms in the general model, turns in roundabouts increase pedestrian-vehicle conflict risk considerably (by 88.2%). Buses are slower than cars in roundabouts, while trucks and PTWs are faster.

3.3.2 Before-after study

The histograms (Figure 7) and Table 9 below show risk indicators both before and after the 4-leg intersection and the old-traffic circle received treatment. In the case of the 4-leg intersection, the treatment lead to a decrease in speeds, from a mean of 17.9 km/h to a mean of 15.4 km/h. The speed distribution for the intersection is clustered around the mean and has a small standard deviation. The treatment led to a clear shift to lower speeds, seen in the left histogram. In the case of the roundabout (old traffic circle), the speed distribution is dispersed, and a clear pattern cannot be observed. But it can be seen that the treatment reduced the number of conflicts where speed exceeds 100 km/h, which represents an improvement in safety for the most severe conflicts.

Table 9: Summary Statistics before and after treatment

Variable	Obs.	Mean	Std. Dev.	Min	Max	Obs.	Mean	Std. Dev.	Min	Max
	Intersection 6 before					Intersection 6 after				
PET (seconds)	3,534	4.43	1.98	0.03	9.97	2,319	4.22	1.74	0.05	9.95
1/PET (1/seconds)	3,534	0.31	0.65	0.10	33.33	2,319	0.30	0.48	0.10	20.00
Speed (Km/h)	3,534	17.89	5.95	1.90	60.26	2,319	15.38	5.86	1.80	46.22
Night Time	3,534	0.22	0.42	0.00	1.00	2,319	0.18	0.39	0.00	1.00
Peak Hour	3,534	0.25	0.43	0.00	1.00	2,319	0.18	0.39	0.00	1.00
Crossing Distance	3,534	12.88	2.34	8	14	2,319	12.16	2.77	8	14
Traffic Volume	3,534	28.44	13.72	2	69	2,319	32.89	15.17	4	86
Vehicle Type	3,534	1.22	0.52	1	4	2,319	1.29	0.57	1	4
Ln (Risk)	3,534	1.45	0.62	-1.41	6.94	2,319	1.31	0.63	-1.06	6.03
Risk (RI)	3,534	5.56	17.98	0.24	1028.67	2,319	4.67	9.63	0.35	414.60
	Intersection 7 before					Intersection 7 after				
PET (seconds)	933	4.24	1.55	0.65	9.50	1,461	4.29	1.51	0.95	9.90
1/PET (1/seconds)	933	0.28	0.14	0.11	1.54	1,461	0.27	0.12	0.10	1.05
Speed (Km/h)	933	39.55	21.77	2.05	118.30	1,461	45.21	15.93	3.89	102.25
Night Time	933	0.19	0.39	0.00	1.00	1,461	0.18	0.39	0.00	1.00

Peak Hour	933	0.22	0.41	0.00	1.00	1,461	0.23	0.42	0.00	1.00
Crossing Distance	933	9.92	1.37	8.5	13.5	1,461	10.64	1.80	8.5	13.5
Traffic Volume	933	165.21	59.33	19	367	1,461	179.76	68.13	19	421
Vehicle Type	933	1.22	0.70	1	4	1,461	1.20	0.64	1	4
Ln (Risk)	933	2.16	0.76	-0.83	4.54	1,461	2.35	0.58	-0.50	3.92
Risk (RI)	933	11.36	9.37	0.44	93.37	1,461	12.27	6.91	0.61	50.40

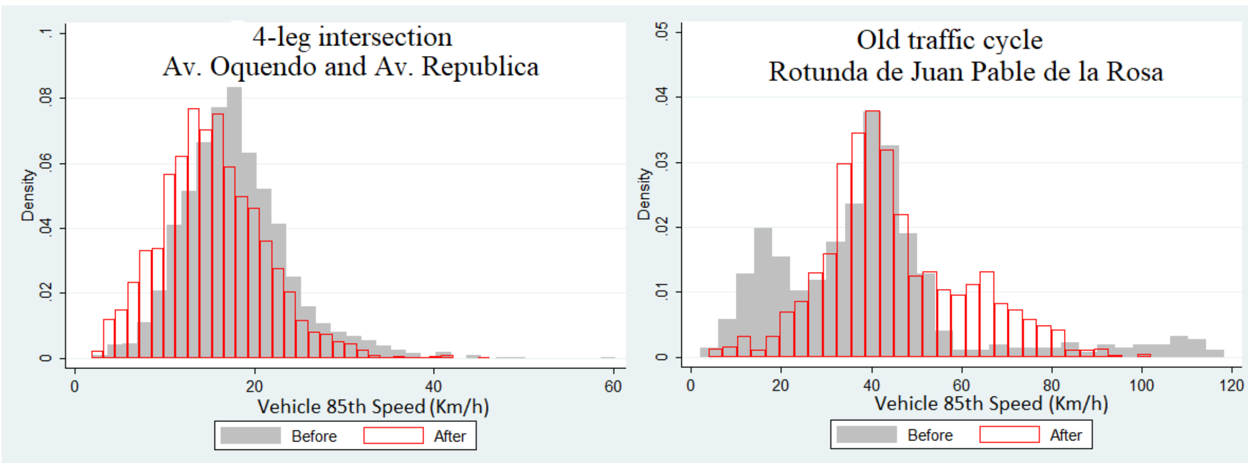


Figure 7: Before-After speed histograms

The risk categories, defined previously, for the traffic circle and the four-leg intersection, both before and after treatment are illustrated in Figure 8 and summarized in Figure 9 for simplicity. Each point represents a single event between a pedestrian and vehicle with a PET < 10s.

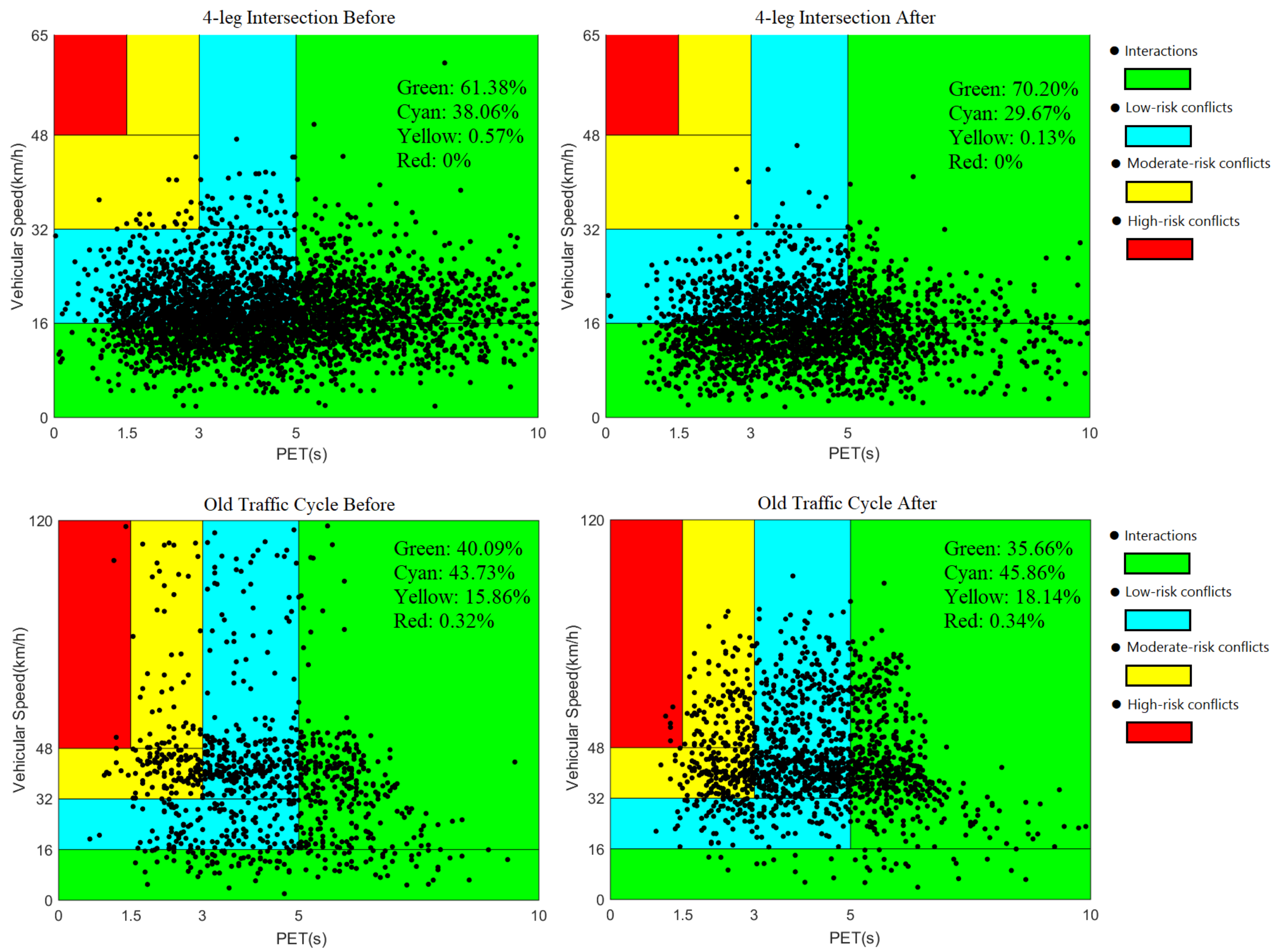


Figure 8: Severity of car-pedestrian conflicts before and after treatment

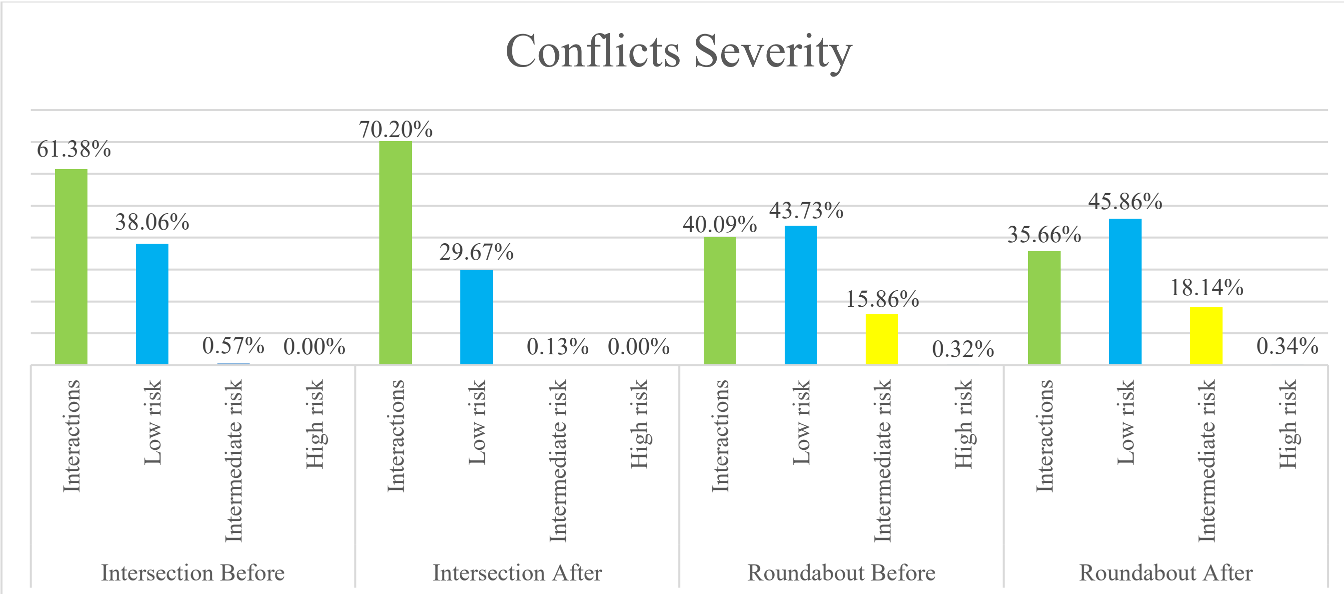


Figure 9: Severity of car-pedestrian conflicts before and after treatment

It is observed that for the 4-leg intersection, there is a decrease in the number of moderate risk (yellow) and low risk (cyan) conflicts, and an increase in the interactions (green), indicating that the treatment was effective. For the traffic circle, the number of high-risk conflicts (red) remains almost unchanged, while there was a shift in proportion of non-dangerous interactions to low and moderate risk conflicts, which implies that the treatment did not improve safety. However, fewer events occurred at excessive speeds (>100 km/h). The following regression models; Tables 10 and 11; were generated to further analyze the effect of treatment. The parameter "treated" denotes whether the interaction corresponds to before or after the treatment, where "treated=0" denotes before, and "treated=1" denotes after.

Table 10: General models

	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se
Night-time	-0.067***	-0.021	-0.511*
	(0.018)	(0.015)	(0.291)
Peak-hour	0.036**	-0.006	1.024***
	(0.017)	(0.014)	(0.275)
Crossing Distance	0.040***	0.003	1.557***
	(0.004)	(0.003)	(0.062)
Traffic Volume	0.000	-0.000	0.024***
	(0.000)	(0.000)	(0.003)
Bus	-0.118***	-0.025	-0.542
	(0.022)	(0.018)	(0.364)
Truck	-0.050	-0.034	2.156***
	(0.033)	(0.027)	(0.539)
PTW	0.392***	0.424***	6.401***
	(0.063)	(0.052)	(1.042)
Turning Movement	-0.231***	-0.026	-7.105***
	(0.020)	(0.017)	(0.333)
Roundabout	0.199***	-0.055	7.715***
	(0.042)	(0.034)	(0.688)
Turning Movement # Roundabout	0.923***	0.045	23.424***
	(0.043)	(0.035)	(0.704)
Treated	-0.060***	-0.003	-0.597***
	(0.014)	(0.011)	(0.228)
Constant	1.073***	0.301***	0.718
	(0.043)	(0.035)	(0.711)
Observations	8247	8247	8247

Table 11: Intersections and roundabouts only models

	Intersections only models			Roundabouts only models		
	Ln (risk)	1/PET	RU2 85th Speed	Ln(risk)	1/PET	RU2 85th Speed
	b/se	b/se	b/se	b/se	b/se	b/se
Night-time	-0.067***	-0.012	-0.799***	-0.110***	-0.022***	-0.649
	(0.022)	(0.021)	(0.200)	(0.033)	(0.007)	(0.914)
Peak-hour	0.005	-0.005	-0.125	0.101***	0.006	3.811***
	(0.020)	(0.019)	(0.185)	(0.030)	(0.006)	(0.834)
Traffic Volume	-0.002***	0.000	-0.054***	0.001***	0.000	0.051***
	(0.001)	(0.001)	(0.006)	(0.000)	(0.000)	(0.006)
Bus	-0.096***	-0.024	-0.157	-0.400***	-0.003	-9.083***
	(0.023)	(0.022)	(0.215)	(0.083)	(0.018)	(2.327)
Truck	-0.146***	-0.055	0.117	0.181***	0.016	6.264***
	(0.039)	(0.037)	(0.360)	(0.059)	(0.012)	(1.650)
PTw	0.725***	1.850***	5.494***	0.327***	0.060***	7.263***
	(0.141)	(0.134)	(1.290)	(0.069)	(0.015)	(1.936)
Crossing distance	0.017***	0.003	0.540***			
	(0.004)	(0.004)	(0.039)			
Turning Movement				0.688***	0.018**	17.057***
				(0.039)	(0.008)	(1.084)
Right Turn	-0.146***	-0.025	-3.405***			
	(0.023)	(0.022)	(0.214)			
Left Turn	-0.175***	-0.017	-4.447***			
	(0.027)	(0.026)	(0.246)			
Treated	-0.124***	0.003	-2.097***	0.111***	-0.009*	3.088***
	(0.017)	(0.016)	(0.153)	(0.025)	(0.005)	(0.703)
Constant	1.429***	0.281***	14.964***	1.435***	0.257***	16.314***
	(0.058)	(0.055)	(0.534)	(0.043)	(0.009)	(1.205)
Observations	5853	5853	5853	2394	2394	2394

The effect of the treatment for the 4-leg intersection was a decrease in collision risk, consistent with what was seen in the summary statistics. The treatment has a significant effect on vehicle velocity, with an estimated reduction of 2.1 km/h, or 12%. Furthermore, the risk ratio decreased by 12.4% (see Table 10).

For the traffic circle, the treatment appears to have increased collision risk. PET increased slightly but the speed increased by 3.1 km/h, or 8%. The risk ratio increased by 11.1%. From the recorded video data, it can be seen that there is a prevalence of traffic law infractions, which is likely to be the reason of the increase of risk in the traffic circle. The treatments applied in the case study were insufficient and additional interventions are needed. The vehicles may have been encouraged to go faster because of the lane markings treatment, which led to a negative impact when pedestrians are crossing. Vehicle speeds in the traffic circle are significantly higher than in the intersection and geometric design changes are required to make the traffic circle safer by transforming it into other safer types of intersections or by improving the separation between vehicles and vulnerable road users.

Chapter 4 PTWs risk contributing factors

4.1 METHODOLOGY

The research method was implemented in four stages: 1) site selection and data collection, 2) video processing, 3) data preparation and 4) regression and behavioral analysis as presented in Figure 10.

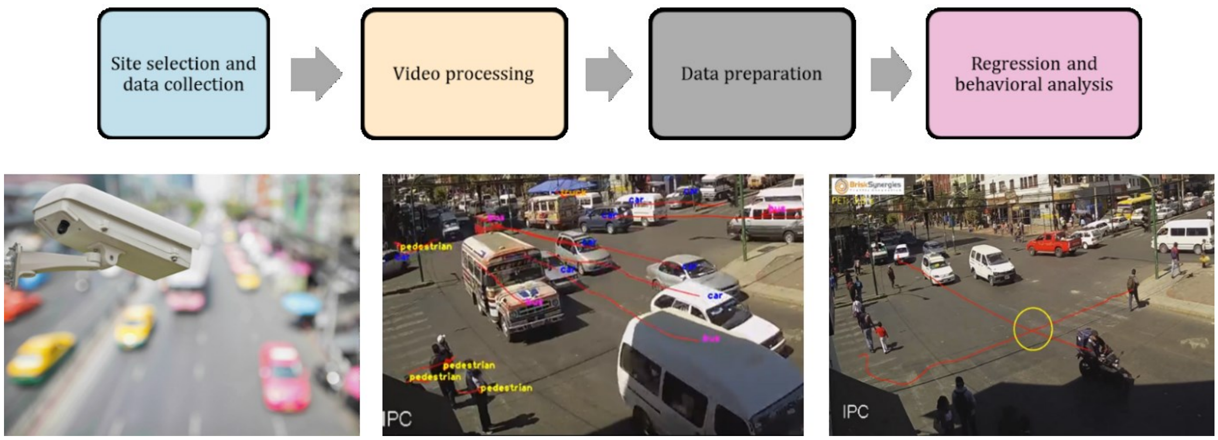


Figure 10: Methodology

4.1.1 Site selection and data collection

Six sites were selected, depending on the data availability in Cochabamba and Bogota, to analyze the factors affecting PTWs risk. The sites include the three most common types of intersections in Cochabamba, which are 3-leg intersections, 4-leg intersections and roundabouts, and include a road segment in Bogota characterized by the high percentage of PTWs among its road users and the risky behavior of the drivers. Detailed description of the sites is provided in Figure 11 and Table 13. Data was collected using temporarily installed high-definition video cameras, with a 2048x1536 resolution and 30 fps, at lamp posts or buildings. The cameras were installed at a minimum height of five meters and were removed after the completion of data collection.

Figure 11: Selected sites

4.1.2 Video processing

Video processing was done in three steps using a computer vision software solution, *Brisk Lumina*, (Brisk Synergies, n.d.) which applies deep and machine learning algorithms for traffic safety analysis. First, the definition of scenarios of interest was conducted. A traffic scenario is composed of an interaction between a PTW and another road user that generates crash risk exposure. The interactions can include the crossing paths of a PTW with a motor-vehicle (truck, bus, car or a second PTW), a cyclist or a pedestrian. Second, the videos were calibrated by adjusting homography, defining the conflict zones, and learning from image datasets. Homography corresponds to the identification of the points in the video corresponding to the street coordinates by comparing two images of the same planar surface in space that are related to each other (St-Aubin et al., 2018). Lastly, road users are detected, tracked, classified and various variables are generated for each. Trajectories (position and speed at each frame) are also extracted from the video footage. The road users detection and classification utilize a deep learning neural network capable of detecting different types of objects (e.g. truck, bus, car, PTWs, pedestrian, etc.). For improving detection and classification accuracy, the network has been trained on many large-scale datasets. The videos processed in this study are 30 frames per second. The software outcomes are trajectories classified by road user type, speeds, PET events and 10 second video clips with recorded conflicts with a PET < 10 seconds.

4.1.3 Data preparation and SMS preparation

Among the surrogate safety indicators, speed is one of the main indices used in this research. In conflicts with PTWs, pedestrians and cyclists are most exposed to collision-related dangers. PTW speeds are more relevant to determining the risk level than pedestrians or cyclists speed. For vehicle-PTW collisions, the speed of the vehicle has a big impact on risk, as the PTW is the more vulnerable road user and the one more susceptible to fatal injuries. It is also important to consider the order of arrival to the conflict point as well as the angle of collision. For frontal collisions, the sum of the vehicle and the PTW speeds should be considered, for rear-end collisions, the speed of the road user arriving last to the conflict point is more important, and for angle collisions, the relevant speed would depend on the angle of the collision. However, we are unable to determine whether the collision is more likely to be a frontal, a rear-end or an angle collision using our data. For our conflict analysis, we use the speed of the PTW as the surrogate safety indicator for all conflicts.

Median, 85^{th} and 15^{th} percentiles of observed speeds were automatically generated by the software for all road users using trajectory data. Additionally, PET was also generated, and by combining the 85^{th} percentile of PTW speed and PET, we generated a simple risk index (RI=85^{th} PTW Speed/PET). The 85^{th} speed, and similarly the 15^{th} speed, are defined as the 85^{th} and 15^{th} percentiles, respectively, of speed of all instantaneous speeds of a single trajectory, and PET is defined as the time difference between when the first road user leaves the conflict area (t1) and when the second road user enters the same area (t2), or PET= t2 – t1. The smaller the PET, the higher the probability of collision is between the two road users, making it a good surrogate indicator for conflict analysis. Similarly, speed can be used as an indicator of the crash potential between road users and as a predictor to the injury severity in case of collisions (Ceunynck, 2017; European traffic Safety Council, 1995).

In our speed and conflict analysis, we examine the effect of various traffic-related factors and conditions in which the interaction took place for the three previously mentioned surrogate safety indices. This regression analysis identifies which of those factors are the ones increase the risk of PTWs. A definition of the indices and potential related contributing factors is presented in Table 12.

Table 12: Variables Description

	Variable	Description	Categories / Units
Safety index	PET	Post-Encroachment Time between two road users	Seconds
	VS_{85}	85^{TH} percentile of the PTW	km/h
	VS_{median}	Median speed of the PTW	km/h
	RI	Risk index (VS_{85}/PET)	Km/h-s
Potentially related factors	Peak hour	Whether the interaction is during peak hours or not (7:00 to 9:00, 15:00 to 17:00)	0 = not peak hours and 1 = peak hours
	Night-time	Whether the interaction is during night-time or not (19:00 to 7:00)	0 = daytime and 1 = night-time
	Weekend	Whether the interaction is during the weekend or not	0 = weekday and 1 = weekend
	Volume	15-min vehicles traffic count	Vehicles
	Road user type	The type of road user involved	Categorical variable with 6 categories: pedestrian, cyclists, car, truck, bus or PTW
	Site Type	Whether the site is an intersection or a roundabout	0 = intersection, 1 = roundabout

From the literature review, it is shown that PTWs have distinguishable characteristics as they are capable of maneuvering between other vehicles and the predominant cause of PTWs crashes is human error and behavioral issues. From the collected video data, we could observe numerous traffic violations by PTW drivers, and multiple serious conflicts were observed when the PTWs are maneuvering between other vehicles to try to reach the front of the queue. As a complementary analysis, a behavioral analysis was carried to investigate the risk contributing factors of PTWs, especially their maneuvering behavior and traffic violations. For this purpose, a sample of the interactions with PET < 3 seconds involving a PTW was selected and video clips of 10 seconds were generated for each of these conflicts. The videos were manually revised and classified in four scenario types as illustrated in the following Figure 12. The objective of this analysis is to observe the relationship between safety indicators, namely PET and speed, the behavior of the drivers and some other factors observed by the manual examination of the conflict videos.

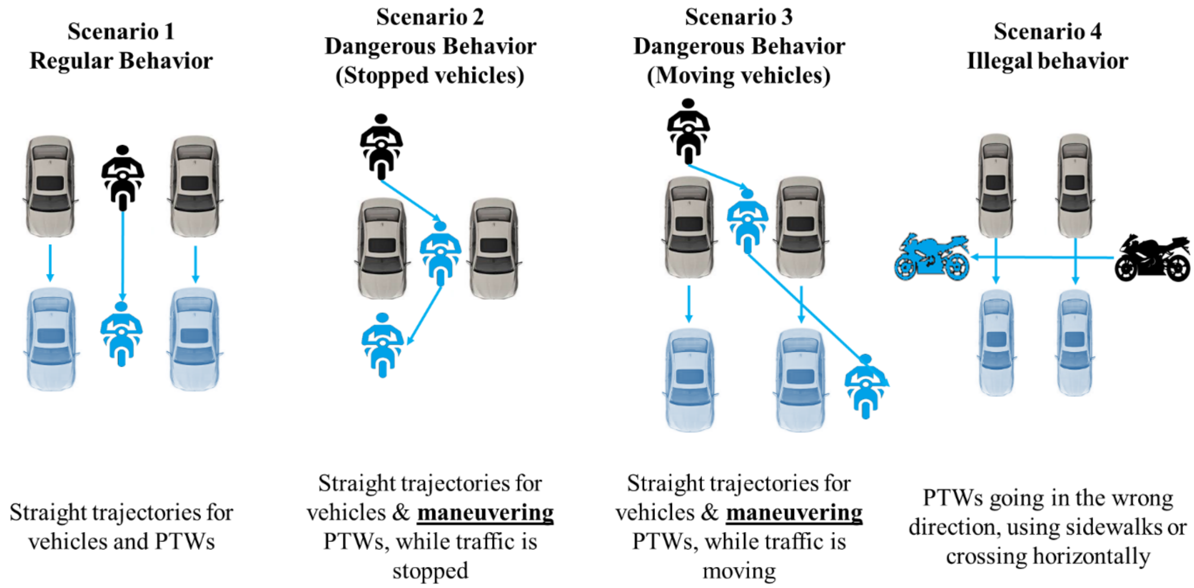


Figure 12: PTWs behavior scenarios

Figure 12 depicts four possible scenarios the PTWs drivers may take. In the figure, cars are used to represent four different types of vehicles for simplicity. The vehicles can be cars, buses, trucks or PTWs. The scenarios are summarized as:

- Scenario 1 is the regular desirable behavior, where PTWs and vehicles travel in straight trajectories, have similar speeds and do not change lanes.
- Scenarios 2 & 3 represent dangerous behavior where the PTWs maneuver their way to the front of the traffic between the other vehicles. The difference between the two scenarios is that in scenario 2, the PTWs maneuver while traffic is stopped, and in scenario 3, the PTWs maneuver while traffic is moving.
- Scenario 4 shows illegal behavior by the PTWs where they use the sidewalks, go in the wrong direction, or cross the street horizontally.

Other factors potentially related to the crash risk were generated for each of the PTWs involved in a conflict event:

- Type of PTW: This is divided into two categories, the first corresponds to smaller PTWs, namely mopeds and scooters which have smaller engines, wheels and overall size and are less expensive. Category two is for the bigger PTWs like motorcycles which have larger engines, bigger frames, and better acceleration than the smaller PTWs.
- Other road user: This is the road user in conflict with the PTW and is divided into three categories: one if it is a vehicle (car, bus, truck or a second PTW), two if it is a pedestrian, and three if it is a cyclist.
- Number of riders: This is one when the driver is alone, and two when the driver is accompanied by a passenger,
- Presence of a helmet: this is zero when either the passenger, the driver or both are not wearing a helmet, and one when all riders are wearing a helmet
- First arrival: this represents which road user arrives first to the conflict point first. It is one if the PTW arrives first, and it is two if the other road user arrives first. In case of crashes, the road user that first arrives would be hit by the road user that arrives after. For PTW-pedestrian interactions, if the PTW arrives first, the risk the pedestrian imposes by arriving after is small, but if a large vehicle arrives after the PTW, it can cause fatal injuries to the PTW driver.

4.1.4 Statistical regression and behavioral analysis

Regression analysis was used to build speed models and conflict models using three surrogate safety indices; 1) the 85th PTW speed, 2) the inverse of PET, and 3) the log of the risk index "Ln(85th Speed/PET)"; for each interaction where PET is less than 10 seconds. From the point of view of safety, lower speeds and higher PETs are desirable, meaning that higher values of speed, 1/PET and subsequently Speed/PET represent higher risk. For the purpose of this study, mixed-effects multi-level linear regression models were built, where higher values of any of the three surrogate safety indices represent higher risk, using the following form:

$$y_{ij} = \beta_0 + \beta_1 x_{ij1} + \beta_2 x_{ij2} + \cdots + \beta_p x_{ijp} + \alpha_j + \varepsilon_{ij}$$

Where:

y_{ij}- surrogate risk indices (ln (RI), 1/PET, and VS_{85})

x_{ijk} - the vector of explanatory variables (road user, peak hour, night-time, traffic volume, site type, etc…)

β_p - the vector of unknown regression parameters

αj – fixed effects error term for each site j

ε_{ij} - error random term of the regression

4.2 DATA GENERATION

From the six study locations (5 in Cochabamba and 1 in Bogota), speed data was generated for more than 350,000 road users. The speed data includes median speed, 85th speed and 15th speed. The road users are divided into either pedestrian, cyclist, PTW, car, truck or bus. In addition, 1,200 conflicts between two road users, where at least one of the two road users was a PTW were detected and a set of variables was generated for the road users including their arrival time, which road user arrives to the conflict point first, movement type of the road user, and the 15-min traffic volume. Only interactions where PET is less than 10 seconds were recorded, as those are the ones that may pose a collision risk and from those, a set of conflicts with PET less than 3 seconds was selected for further manual examination to analyze driver's behavior. During the manual examination, additional variables were generated such as driving scenario, the availability of a helmet, number of riders and the type of PTW.

Table 13: Summary statistics

	Site Type	Median Speed	85th Speed	Observations	Percentage
ID 1: Av. Ayacucho and Av. Punata	Non-signalized intersection	16.24	27.62	76417	21.8%
ID 2: Av. Ayacucho and Av. Aroma	Signalized intersection	17.04	23.60	66621	19.01%
ID 3: Av. Rubén Darío - Jardín Botánico	Roundabout	12.83	20.69	33657	9.60%
ID 4: Av. Oquendo and Av. República	Signalized intersection	9.55	15.70	68236	19.47%
ID 5: Rotunda de Juan Pablo de la Rosa	Roundabout	34.74	49.98	94642	27.00%
ID 6: Bogota road segment	Road Segment	9.84	18.98	10912	3.11%
Total		19.56	29.64	350485	100%

A total of 350,485 road users were detected in our analysis and their average median and 85th speeds by each site are represented in Table 13 above. This includes all road users, not just PTWs, and we can see that the site with the highest number of observations, as well as the highest speeds is site number 5, which is an old traffic circle. Table 14 shows the speed distributions by road user. The most common road users are cars, representing 62.86% of the total road users. PTWs are always the fastest, with an average median speed of 31.1 km/h for all sites and 19.53 km/h for Bogota only. Pedestrians register an average median speed of 5.6 km/h for all sites and 5.71 km/h for Bogota. A very important distinction between the values for all sites and for Bogota only is that the percentage of PTWs for all sites is just 2.06% while for Bogota, 11.29% of road users are PTWs. That shows the importance of the PTWs as a mode of transportation in Bogota.

Table 14: Speed distributions by road user for Bogota only

User Type	Observations	Percentage	Median Speed	85th Speed
	All Sites			
Car	220,309	62.86	24.7	36.5
Bus	18,735	5.35	17.1	27
Truck	9,075	2.59	26.8	41.9
PTW	7,217	2.06	31.1	47.7
Bicycle	11,101	3.17	13.8	23.2
Pedestrian	84,048	23.98	5.6	10.3
Total	350,485	100	19.6	29.6
	Bogota Only			
Car	5295	48.52	9.5	18.15
Bus	282	2.58	7.56	17.13
Truck	625	5.73	10.09	25.62
PTW	1,232	11.29	19.53	34.58
Bicycle	751	6.88	12.01	26.82
Pedestrian	2,727	24.99	5.71	10.05
Total	10912	100	9.84	18.98

4.3 ANALYSIS AND RESULTS

4.3.1 Speed analysis

Speed analysis was conducted first using the more than 350,000 road user observations defined in section 4. Multi-level linear regression models with random effects for each location were fitted to the data. The results of the median and 85th percentile speeds models are reported in Table 15.

Table 15: Speed multi-level mixed effects linear regression models

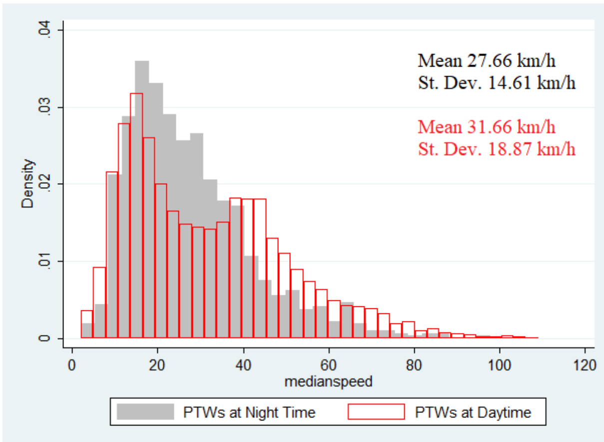
	Median Speed		85th Speed	
	Parameter	**St. Error**	**Parameter**	**St. Error**
Night-time	-0.169***	(0.053)	0.558***	(0.081)
Peak-hour	0.710***	(0.057)	1.374***	(0.087)
Weekend	1.482***	(0.046)	3.135***	(0.070)
Intersection (Base)	-	-	-	-
Roundabout	8.686***	(0.053)	11.482***	(0.081)
Car (Base)	-	-	-	-
Bus	-5.376***	(0.102)	-6.285***	(0.156)
Truck	1.019***	(0.142)	3.955***	(0.217)
PTW	6.644***	(0.159)	11.371***	(0.244)
Bicycle	-6.974***	(0.130)	-8.425***	(0.200)
Pedestrian	-15.083***	(0.059)	-21.059***	(0.091)
Bogota	-6.686***	(0.133)	-6.259***	(0.205)
Constant	19.808***	(0.051)	29.125***	(0.079)
Observations	350,485		350,485	

* p<0.10, ** p<0.05, and *** p<0.01

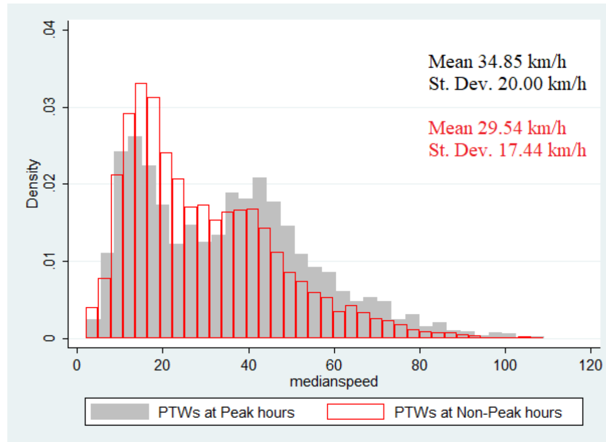
All parameters in the models in Table 15 are statistically significant at the 1% level. From the median speed model, it is observed that night-time causes a decrease in median speed by 0.169

km/h, while peak hours and weekends increase median speed by 0.710 km/h and 1.482 km/h respectively. Consistent with what was found in a previous study in Cochabamba (Scholl et al., 2019), median speeds are higher at roundabouts compared to at intersections by 8.686 km/h and the Bogota road segment has a median speed lower than Cochabamba by 6.686 km/h. The fastest road users are PTWs, followed by trucks, and the slowest are pedestrians then cyclists. Similar results can be observed from the 85^{th} speed model for the fastest and slowest road users. The Bogota road segment has an 85^{th} speed lower than Cochabamba by 6.259 km/h, and the 85^{th} speeds at roundabouts are higher than at intersections by 11.482 km/h. Peak hours and weekends also cause an increase in 85^{th} speed by 1.374 km/h and 3.135 km/h respectively, but unlike with the median speed, night-time leads to an increase in the 85^{th} speed by 0.558 km/h.

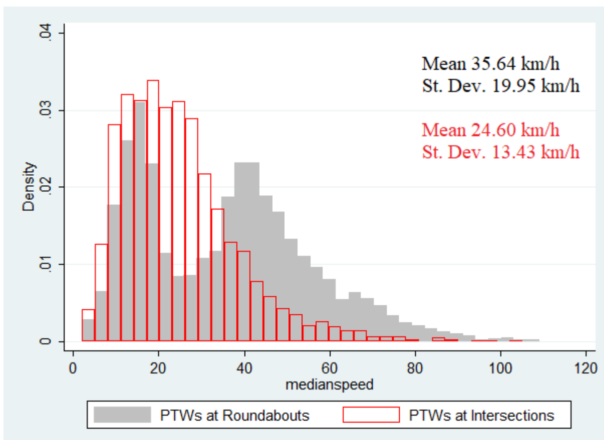
Figure 13 shows multiple speed histograms. In histogram "a", night-time is shown to cause a decrease in median speed as the average median speed at night-time, for PTWs, is 27.66 km/h versus 31.66 km/h at daytime. Histogram "b" shows that peak hours are associated with an increase in median speeds as the average median speed during peak hours, for PTWs, is 34.85 km/h vs 29.54 km/h during non-peak hours. In histogram "c", roundabouts have higher speeds than 3-legged and 4-legged intersections. The average median speed for PTWs at roundabouts is 35.64 km/h compared to 24.6 km/h at intersections. Lastly, histogram "d" compares the median speed of PTWs against other types of vehicles; cars, buses and trucks; and shows that PTWs are the fastest. The average median speed for PTWs 31.1 km/h vs 24.2 km/h for cars, buses or trucks.



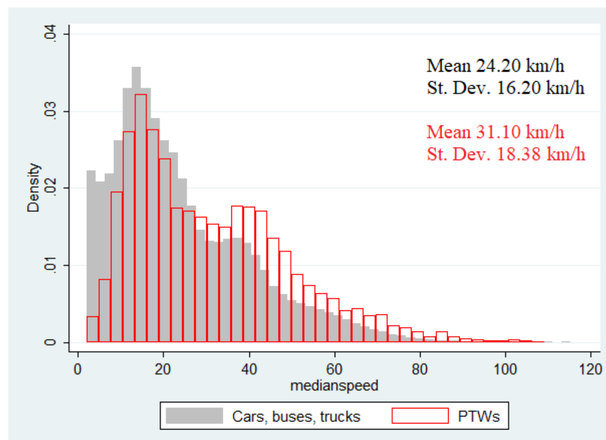
a) Night time vs daytime



b) Peak hours vs non-peak hours



c) Roundabouts vs intersections



d) PTWs vs other vehicles

Figure 13: Speed histograms

4.3.2 Conflict analysis

Multi-level mixed effects linear regression models were also used to analyze 1,200 conflicts all including a PTW road user in conflict with another road user. The road users in conflict with PTWs are divided into three categories: vehicles (car, truck, bus or a second PTW), cyclists and pedestrians. It was observed that the average median speed of vehicles in conflict with PTWs is 9.2 km/h, pedestrians, 5.1 km/h and cyclists, 11.7 km/h as shown in Table 16.

Table 16: Other road users data in conflicts

User Type	Observations	Percentage	Median Speed	85th Speed
Vehicle	643	53.58	9.2	15.3
Pedestrian	473	39.42	5.1	9.7
Cyclist	84	7	11.7	22.5
Total	1200	100	7.8	13.6

The results of the regression analysis are presented in Table 17. From here, we can observe that night-time, peak hour and traffic volume do not have a significant effect on PET. Night-time causes a reduction of speed by 1.835 km/h. Peak hours increase speed by 1.278 km/h and risk by 7.2%. A traffic volume increase by one unit leads to an increase in speed by 0.029 km/h and in risk by 0.2%. PTWs are faster when interacting with pedestrians (by 10.292 km/h) and cyclists (by 15.215 km/h) than when interacting with vehicles. Compared to PTW-vehicle interactions, PTW-pedestrian interactions are 50.9% more risky with a 0.077 sec^{-1} increase in 1/PET and PTW-cyclist interactions are 74.1% more risky with a 0.543 sec^{-1} increase in 1/PET. The Bogota site (road segment), is accompanied by a large reduction in speed by 12.476 km/h, possibly due to congestion, and a decrease in risk by 25.4%.

Table 17: Conflicts multi-level mixed effects linear regression models

	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se
Night-time	-0.053	-0.070	-1.835*
	(0.112)	(0.149)	(1.872)
Peak-hour	0.072**	-0.000	1.278**
	(0.054)	(0.072)	(0.908)
Traffic Volume	0.002***	-0.000	0.029***
	(0.000)	(0.001)	(0.007)
Vehicle (Base)	-	-	-
	-	-	-
Pedestrian	0.509***	0.077**	10.292***
	(0.049)	(0.067)	(0.843)
Cyclist	0.741***	0.543***	15.215***
	(0.098)	(0.134)	(1.702)
Bogota	-0.254***	-0.002	-12.476**
	(0.142)	(0.321)	(9.811)
Constant	1.590***	0.323***	27.520***
	(0.091)	(0.162)	(4.189)
Observations	1200	1200	1200

* p<0.10, ** p<0.05, and *** p<0.01

4.3.3 Behavioral analysis

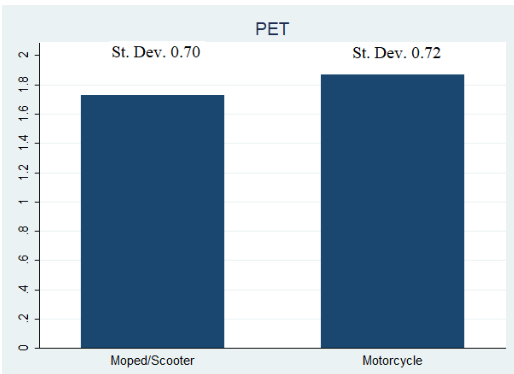
Manual examination was conducted for a set of 157 conflict videos from Bogota where PET is less than 3 seconds for behavioral analysis. The factors defined in the methodology were analyzed and a summary of the results is presented in Table 18. From this, one can observe that for 28% of PTWs, a passenger was accompanying the driver and for 72% the driver was alone. In 58% of the cases, the PTW arrived at the conflict point first, and in the remaining 42% of the cases, the other road user arrived first. We can see that in 3 out of 10 interactions, the PTW driver was making a dangerous maneuver according to scenarios 2 and 3. In 7% of the observations, the PTW was maneuvering while the traffic is stopped and in 23% of the observations, it was maneuvering while the traffic is moving. Most of the road users in conflict with the PTWs are pedestrians, followed by vehicles (car, bus, truck or a second PTW), and lastly cyclists. Forty-six percent of the PTWs were categorized as mopeds or scooters, and 54% were categories as motorcycles. All PTWs riders, whether they are the passenger or the driver, were observed to be wearing helmets.

Table 18: Manual Examination Findings

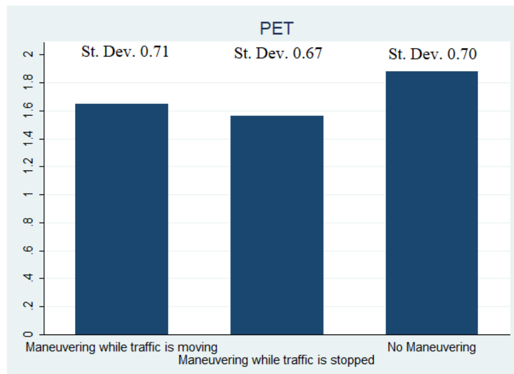
	Categories	Observations	Percentage
Number of riders	One	113	72%
	Two	44	28%
Arrived first	PTW	91	58%
	Other road user	66	42%
Behavior	No Maneuvering	110	70%
	Maneuvering while traffic is moving	36	23%
	Maneuvering while traffic is stopped	11	7%
Other road user	Vehicle	41	26%
	Pedestrian	106	68%
	Cyclist	10	6%
Vehicle Type	Moped/Scooter	73	46%
	Motorcycle	84	54%
Wearing Helmet	Yes	157	100%
	No	0	0%

Mixed effects regression models were used to check the significance of the parameters in Table 18 on speed and PET for the 157 conflicts used in the behavioral analysis. It was found that the number of riders, the type of road user in conflict with the PTW and who arrives to the conflict point first do not have a significant effect on speed and PET. Maneuvering while traffic is moving has a statistically significant effect on PET at the 4% level, and maneuvering while traffic is stopped has an effect on PET at the 15% level and on speed at the 8% level. The type of vehicle also had a statistically significant effect on PET at the 8% level.

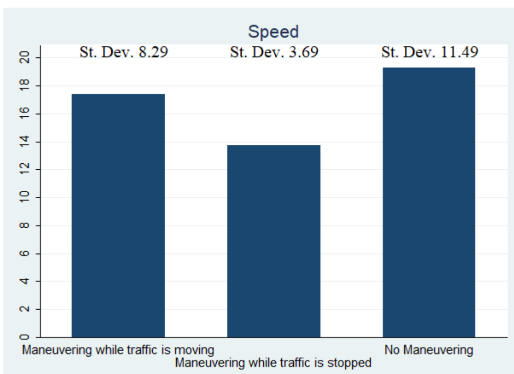
The significant factors detailed above are compared in Figure 14. It can be observed that moped/scooters (the smaller PTWs) have lower PET, making them more dangerous than motorcycles (the larger PTWs). The average PET of smaller PTWs is 1.728 seconds compared with 1.869 seconds for the larger PTWs. Additionally, it was found that maneuvering causes a significant reduction in PET, whether the traffic is moving or not, and when drivers maneuver while traffic is moving, they only slightly slow down, making it a dangerous action. When there is no maneuvering, the average PET is 1.878 seconds, and average median speed is 19.312 km/h, when PTWs are maneuvering between the moving traffic, the average PET is 1.651 seconds, and average median speed is 17.381 km/h and finally, when PTWs are maneuvering between the stopped traffic, the average PET is 1.561 seconds, and average median speed is 13.765 km/h.



a) PET by type of PTW



b) PET by scenario



c) Median speed by scenario

Figure 14: PET & speed comparison for different scenarios and types of PTWs

Chapter 5 Conclusions and future work

5.1 CONCLUSIONS

This thesis presents a proactive surrogate safety methodology for identifying pedestrians and PTWs risk factors. This work also evaluates low-cost temporary countermeasures at intersections for improving pedestrian safety in the LA context. Using road user trajectories obtained from video-analysis software, speeds and conflicts were automatically generated for thousands of vehicle-pedestrian interactions. In addition to the risk indicators, a set of variables for interactions including a pedestrian or a PTW were generated, which includes event-related variables and geometric features.

In the first part of this thesis, and once data was prepared, a regression analysis was executed considering only the pedestrian-vehicle interactions with a PET<10 seconds and those events in which the pedestrian arrives first to the collision point. Regression models were developed for a simple risk ratio that combines the product of the inverse of the PET value and the 85^{th} vehicle speed for each event. Various factors were identified as significantly related to the surrogate indicators. Compared to other motor-vehicle types, PTWs pose a serious threat to traffic safety given their tendency to speed. This is an interesting observation given the increasing use of PTWs traffic in many Latin American cities and the emerging safety issues. PTWs are seen as not only the most dangerous transportation mode but also a mode deteriorating the safety of active road users (pedestrians and cyclists).

With respect to other intersection types and pedestrian safety, the multilane old-traffic circle examined in this study was found to be the most dangerous intersection across all safety indicators. This is not surprising given the vehicle operating speeds and volumes that are much higher than regular intersections along with the larger crosswalk crossing distances. These three key risk-exposure factors (high speeds with large volumes and crossing distances) make traffic circles a high-risk location for pedestrians in cities like Cochabamba. As an additional note, the most dangerous vehicle movements were identified as left-hand turns at standard intersections and turning in and out of roundabouts.

In the before-after analysis, only low-cost provisional treatments in the four-way intersection were effective at reducing speeds and risk, while in the traffic circle, the treatment had a slightly negative impact on pedestrian crash risk. This suggests that low-cost treatments might not be effective in traffic circles. Given the complexity of the traffic safety problem at those locations, more complex design treatments could be evaluated in the future. This could include the transformation of old-traffic circles into modern roundabouts/intersections in which designs consider pedestrian safety as a priority. This could be particularly important in urban locations with high pedestrian volumes.

In the second part of the thesis, the risk factors and dangerous behaviors of PTWs are investigated using a similar methodology based on surrogate safety methods. Among main conclusions, it was found that PTWs are the fastest road users, from all motorized modes, with an important proportion exceeding speed limits. PTW speeds were also found to be higher during peak hours and lower during night-time, and PTWs are faster when interacting with pedestrians or cyclists than with other vehicles. Given the vulnerability of non-motorized road users, PTWs operating speeds pose a real danger to pedestrians. In the study locations, Bogota has a significantly higher percentage of PTWs in its streets, 11%, compared to an average of 2% for Cochabamba.

From the behavioral analysis and direct observations from conflict-video clips, smaller PTWs (moped/scooters) were more dangerous than larger PTWs (motorcycles) in terms of PET. A lot of traffic violations were observed as drivers maneuver between moving and not moving traffic to get to the front of the queues. Maneuvering PTWs have smaller PETs and slow down only slightly, making their behavior dangerous. Wearing a helmet is mandatory. Interestingly, in Bogota most of the observed motorcyclists were wearing helmets, which is different from our observations in Cochabamba.

To address the safety issue, PTWs behavioral aspects must be addressed. Currently, many LA countries are starting to implement new policies to deal with the risk of PTWs. For instance, the Bogota motorcyclist road safety plan proposes 100 actions to deal with the safety problem, including the reduction and enforcement of speed limits (e.g., to a max of 60 km/h), which could be reinforced with the installation of mobile radars to take constant measurements. To prevent dangerous behaviors, speeding and violations, video camera systems and license plate recognition would be required to detect PTWs. This could be problematic as plates are sometimes difficult to detect. In Bogota, motor-vehicles usage is restricted during some days of the week based on the last digits of the license plate to reduce traffic congestion and air pollution (Bonilla, 2016). PTWs are currently excluded from that policy, making them a more attractive mean of transport, therefore leading to an increased use. Opinions about PTWs are divided between different social classes as in Bogota for example, 91% of PTW owners belong to the lower social classes (Secretaría Distrital de Movilidad, 2017). Thus, restrictions on PTWs ownership are expected to receive a backlash from the lower income groups and support from the wealthier groups. The policies to regulate or improve the safety of PTWs are still limited especially in the less developed Latin American cities.

Perhaps the most important contributions of this research are the proposition and implementation of a proactive surrogate safety methodology in medium-sized cities in developing LA countries. The evaluation of temporary countermeasures using rapid, low-cost surrogate analysis, before the installation of permanent treatments, can lower the potential risk of misallocation of scarce resources for road safety treatments and can potentially improve overall program effectiveness. The proposed methodology could be replicated in other studies or cities to evaluate alternative temporary (or permanent) treatments. This methodology also aims at introducing the concept of temporary low-cost designs that should be evaluated in a short period of time to minimize injury risk, and before treatments are replicated on a large scale in cities.

5.2 FUTURE WORK

Several limitations of this research can be addressed as part of future work. From the treatment effectiveness point of view, the results should be taken with caution given that the sample of locations involved in this study is small and is not representative of all city intersections. The same caution applies to the risk factors; a larger sample of intersections from the same city or other cities could be integrated in the analysis before coming with general conclusions. Validation of the surrogate safety measures using crash data could also be done in the future using longer-term video data in which both crashes and conflicts can be observed. Future research is needed to further explore the validation of surrogate safety measures, and to compare surrogate indicators with actual crash events.

Different types of regression models need to be evaluated to find the most fitting ones. Some of the models that were examined and were found not to be the best are attached in the appendix. Bigger sample size, especially for the PTWs behavioral analysis, can lead to more accurate and informative results. Due to the lack of adequate PTWs conflict videos from the Cochabamba sites, the behavioral analysis was conducted only for Bogota. Comparing different traffic environments, for example, the high percentage of PTWs in Bogota and normal percentage of PTWs in Cochabamba, is required to better understand the PTWs risk contributing factors.

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Appendix: Additional regression models

The following models are all linear regression models with intersection fixed effects using the three surrogate risk indicators discussed previously to identify risk factors. Linear regression models were used in the analysis where a linear relationship was assumed between the dependent variable (PET, speed or ln (Risk)), and the independent variables:

$$y_i = \beta_0 + \beta_1 x_{i\,1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip} + \alpha Zi + \varepsilon_i$$

, i=1, 2,…..,n

Where:

y_i- surrogate risk measures (ln (RI=V/PET), 1/PET, and V), for all vehicle-pedestrian interactions where PET is less than 10 seconds and the in which the pedestrian arrives before the vehicle.
x - the vector of explanatory variables (in this case, night time, peak hour, intersection type)
Z_i - represents intersection fixed effects
β – is the vector of unknown parameters
ε – represents the random error of the regression estimate

Tables 19 and 20 correspond to tables 7 and 8 respectively. They represent the regression models for the before-only analysis using fixed effects models instead of multi-level mixed effect models and they show similar results.

Table 19: Fixed effects before-only general models

	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se
Night-time	-0.024**	-0.005	0.033
	(0.010)	(0.004)	(0.188)
Peak-hour	0.039***	0.003	0.612***
	(0.011)	(0.005)	(0.199)
Traffic Volume	0.000	-0.000***	0.041***
	(0.000)	(0.000)	(0.003)

Bus	-0.156***	-0.011**	-3.337***
	(0.013)	(0.005)	(0.238)
Truck	-0.010	0.009	-1.322**
	(0.032)	(0.014)	(0.591)
PTW	0.599***	0.238***	15.176***
	(0.050)	(0.021)	(0.937)
Crossing Distance	-0.014***	0.001	0.033
	(0.004)	(0.002)	(0.079)
Turning Movement	0.112***	0.029***	-0.414
	(0.015)	(0.006)	(0.281)
Roundabout	-0.323***	0.052***	-14.804***
	(0.046)	(0.020)	(0.859)
Turning Movement # Roundabout	0.815***	-0.002	22.962***
	(0.051)	(0.022)	(0.952)
Intersection 1	0.000	0.000	0.000
	(.)	(.)	(.)
Intersection 2	-0.136***	-0.004	-7.564***
	(0.014)	(0.006)	(0.260)
Intersection 3	-0.539***	-0.009	-15.494***
	(0.046)	(0.020)	(0.851)
Intersection 4	-0.245***	0.038***	-11.751***
	(0.018)	(0.008)	(0.335)
Intersection 5	0.000	0.000	0.000
	(.)	(.)	(.)
Constant	1.819***	0.246***	28.547***
	(0.043)	(0.019)	(0.808)
Observations	24215	24215	24215

Table 20: Fixed effects before-only intersections & roundabouts only models

	Intersections only models			Roundabouts only models		
	Ln(risk)	1/PET	85th Percentile Speed	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se	b/se	b/se	b/se
Night-time	-0.023**	-0.005	0.075	-0.057	-0.008	-0.625
	(0.010)	(0.004)	(0.183)	(0.046)	(0.011)	(1.233)
Peak-hour	0.041***	0.004	0.573***	0.087**	0.011	2.170**
	(0.011)	(0.005)	(0.197)	(0.040)	(0.009)	(1.089)
Traffic Volume	-0.001***	-0.001***	0.016***	0.002***	0.000***	0.067***
	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.007)
Bus	-0.164***	-0.012**	-3.459***	-0.169*	0.013	-4.082*
	(0.013)	(0.006)	(0.231)	(0.087)	(0.020)	(2.343)
Truck	-0.058*	0.010	-2.924***	0.098	-0.005	6.396**
	(0.033)	(0.015)	(0.596)	(0.093)	(0.021)	(2.501)
PTW	0.609***	0.290***	15.244***	0.357***	0.060***	11.082***
	(0.057)	(0.025)	(1.032)	(0.093)	(0.021)	(2.506)
Crossing distance	-0.031***	-0.000	-0.569***			
	(0.004)	(0.002)	(0.080)			
Signalized Intersection	-0.199***	0.041***	-10.097***			
	(0.018)	(0.008)	(0.325)			
Right Turn	-0.120***	0.024***	-5.471***			
	(0.018)	(0.008)	(0.329)			
Left Turn	0.162***	0.018***	1.550***			
	(0.016)	(0.007)	(0.289)			
Turning Movement				0.883***	0.020*	22.068***
				(0.044)	(0.010)	(1.195)
Intersection 1	0.000	0.000	0.000			
	(.)	(.)	(.)			

Intersection 2	0.130***	-0.037***	3.984***			
	(0.016)	(0.007)	(0.296)			
Intersection 3				0.000	0.000	0.000
				(.)	(.)	(.)
Intersection 4	0.000	0.000	0.000			
	(.)	(.)	(.)			
Intersection 5				0.364***	-0.017*	13.836***
				(0.043)	(0.010)	(1.158)
Constant	2.093***	0.272***	36.662***	0.736***	0.250***	-3.975***
	(0.046)	(0.020)	(0.834)	(0.057)	(0.013)	(1.525)
Observations	22959	22959	22959	1256	1256	1256

Tables 21 and 22 correspond to tables 10 and 11 respectively. They represent the regression models for the before-after analysis using fixed effects models instead of multi-level mixed effect models and they show similar results.

Table 21: Fixed effects before-after general models

	Ln(risk)	1/PET	85^{th} Percentile Speed
	b/se	b/se	b/se
Night-time	-0.067***	-0.021	-0.511*
	(0.018)	(0.015)	(0.292)
Peak-hour	0.036**	-0.006	1.024***
	(0.017)	(0.014)	(0.276)
Traffic Volume	0.000	-0.000	0.024***
	(0.000)	(0.000)	(0.003)
Bus	-0.118***	-0.025	-0.542
	(0.022)	(0.018)	(0.365)

Truck	-0.050	-0.034	2.156***
	(0.033)	(0.027)	(0.539)
PTW	0.392***	0.424***	6.401***
	(0.064)	(0.052)	(1.043)
Crossing Distance	0.040***	0.003	1.557***
	(0.004)	(0.003)	(0.062)
Turning Movement	-0.231***	-0.026	-7.105***
	(0.020)	(0.017)	(0.333)
Roundabout	0.199***	-0.055	7.715***
	(0.042)	(0.034)	(0.689)
Turning Movement # Roundabout	0.923***	0.045	23.424***
	(0.043)	(0.035)	(0.705)
Intersection 4	0.000	0.000	0.000
	(.)	(.)	(.)
Intersection 5	0.000	0.000	0.000
	(.)	(.)	(.)
Treated	-0.060***	-0.003	-0.597***
	(0.014)	(0.011)	(0.229)
Constant	1.073***	0.301***	0.718
	(0.043)	(0.036)	(0.711)
Observations	8247	8247	8247

Table 22: Fixed effects before-after intersections & roundabouts only models

	Intersections only models			Roundabouts only models		
	Ln(risk)	1/PET	85th Percentile Speed	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se	b/se	b/se	b/se
Night-time	-0.067***	-0.012	0.075	-0.110***	-0.022***	-0.649
	(0.022)	(0.021)	(0.183)	(0.033)	(0.007)	(0.916)
Peak-hour	0.005	-0.005	0.573***	0.101***	0.006	3.811***
	(0.020)	(0.019)	(0.197)	(0.030)	(0.006)	(0.836)
Traffic Volume	-0.002***	0.000	0.016***	0.001***	0.000	0.051***
	(0.001)	(0.001)	(0.003)	(0.000)	(0.000)	(0.006)
Bus	-0.096***	-0.024	-3.459***	-0.400***	-0.003	-9.083***
	(0.024)	(0.022)	(0.231)	(0.083)	(0.018)	(2.332)
Truck	-0.146***	-0.055	-2.924***	0.181***	0.016	6.264***
	(0.039)	(0.037)	(0.596)	(0.059)	(0.012)	(1.653)
PTW	0.725***	1.850***	15.244***	0.327***	0.060***	7.263***
	(0.141)	(0.134)	(1.032)	(0.069)	(0.015)	(1.940)
Crossing distance	0.017***	0.003	-0.569***			
	(0.004)	(0.004)	(0.080)			
Right Turn	-0.146***	-0.025	-3.405***			
	(0.023)	(0.022)	(0.214)			
Left Turn	-0.175***	-0.017	-4.447***			
	(0.027)	(0.026)	(0.247)			
Turning Movement				0.688***	0.018**	17.057***
				(0.039)	(0.008)	(1.086)
Intersection 4	0.000	0.000	0.000			
	(.)	(.)	(.)			
Intersection 5				0.000	0.000	0.000
				(.)	(.)	(.)

Treated	-0.124***	0.003	-2.097***	0.111***	-0.009*	3.088***
	(0.017)	(0.016)	(0.154)	(0.025)	(0.005)	(0.705)
Constant	1.429***	0.281***	14.964***	1.435***	0.257***	16.314***
	(0.059)	(0.055)	(0.535)	(0.043)	(0.009)	(1.207)
Observations	5853	5853	5853	2394	2394	2394

For the PTWs analysis, speed fixed effects linear regression models were generated for the median and 85th speeds, as shown in table 23 that can be compared to table 15. Table 24 shows fixed effects linear regression models corresponding the conflicts analysis models for PTWs presented in table 17. The new models show similar, but less accurate, results compared to the original models presented in Chapter 4.

Table 23: Speed fixed effects linear regression models

	Median Speed		85^{th} Speed	
	Parameter	**St. Error**	**Parameter**	**St. Error**
Night-time	-0.200***	(0.047)	0.116	(0.074)
Peak-hour	0.783***	(0.051)	1.299***	(0.080)
Weekend	0.398***	(0.043)	0.964***	(0.067)
Intersection (Base)	-	-	-	-
Roundabout	12.344***	(0.064)	13.428***	(0.100)
Car (Base)	-	-	-	-
Bus	-3.365***	(0.092)	-3.967***	(0.143)
Truck	-0.325**	(0.127)	1.954***	(0.199)
PTW	5.537***	(0.142)	9.885***	(0.223)
Bicycle	-7.518***	(0.118)	-10.663***	(0.185)
Pedestrian	-14.291***	(0.055)	-20.716***	(0.086)
Intersection 1	-	-	-	-
Intersection 2	-2.398***	(0.066)	-8.479***	(0.104)
Intersection 3	-21.458***	(0.076)	-28.537***	(0.118)
Intersection 4	-4.938***	(0.063)	-9.329***	(0.099)
Intersection 5	-	-	-	-
Bogota	-9.174***	(0.126)	-12.601***	(0.197)
Constant	22.255***	(0.063)	35.801***	(0.099)
Observations	350,485		350,485	

* p<0.10, ** p<0.05, and *** p<0.01

Table 24: Conflicts fixed effects linear regression models

	Ln(risk)	1/PET	85th Percentile Speed
	b/se	b/se	b/se
Night-time	-0.033	0.196	-1.861
	(0.113)	(0.312)	(1.878)
Peak-hour	0.069	0.017	1.265
	(0.055)	(0.151)	(0.911)
Traffic Volume	0.002***	-0.002*	0.029***
	(0.000)	(0.001)	(0.007)
Vehicle (Base)	-	-	-
	-	-	-
Pedestrian	0.496***	-0.362**	10.172***
	(0.051)	(0.141)	(0.847)
Cyclist	0.678***	-0.397	14.879***
	(0.103)	(0.285)	(1.713)
Intersection 1	-	-	-
	-	-	-
Intersection 2	-0.486***	0.629	-18.112***
	(0.155)	(0.428)	(2.578)
Intersection 3	-0.353**	-0.493	-22.928***
	(0.143)	(0.394)	(2.371)
Intersection 4	-0.183	-0.361	-20.263***
	(0.155)	(0.427)	(2.567)
Intersection 5	0.009	-0.484	-0.386
	(0.170)	(0.468)	(2.814)
Bogota	-0.462***	-0.317	-24.854***
	(0.120)	(0.331)	(1.994)
Constant	1.818***	4.993***	40.071***
	(0.122)	(0.337)	(2.031)
Observations	1200	1200	1200

* $p<0.10$, ** $p<0.05$, and *** $p<0.01$