**Revista Colombiana de Estadística - Applied Statistics**
January 2021, volume 44, issue 1, pp. 91 a 121
http://dx.doi.org/10.15446/rce.v44n1.81937

# Complete-Linkage Clustering Analysis of Surrogate Measures for Road Safety Assessment in Roundabouts

## Análisis de conglomerados mediante vecinos más lejanos en medidas sustitutas para la evaluación de seguridad vial en glorietas

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### Abstract

This paper presents the findings of a comparative road safety assessment between an existing two-lane roundabout and proposed basic turbo-roundabout, both designed for the same intersection, to determine which one is safer, based on traffic conflicts and surrogate safety measures. We performed microsimulation models in VISSIM to replicate the field-observed traffic operation, and the SSAM to determinate six surrogate measures. We validated the consistency of values obtained by several statistical analyzes. The number of conflicts was 72% lower at the turbo-roundabout. Through a complete-linkage clustering analysis and Euclidean distances of the surrogate measures, we found that traffic conflicts at the turbo-roundabout tend to cluster in a group, whereas conflicts at the roundabout are scattered, suggesting better organization of traffic flows at the turbo-roundabout. Three-dimensional graphical analysis of clusters and its centroids allowed verifying that surrogate measures point out a safer operation at the turbo-roundabout, even though it presented higher operating speeds. Reducing the dimensionality by principal components analysis, the cumulative variance for the first two components (87.72%) allowed observing results on a two-dimensional graph and their clusters. To endorse conflicts classification, resulting of clusters, we used discriminant

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analysis. Results validate the methodology and the safety benefits of the turbo-roundabout.

***Key words*:** Cluster analysis; Complete linkage; Discriminant analysis; Principal Component analysis; Traffic safety simulation.

### Resumen

Este artículo presenta los hallazgos de una evaluación comparativa de seguridad vial entre una glorieta clásica existente y una turboglorieta propuesta, en la misma intersección, para determinar cuál es más segura, con base en conflictos de tráfico y medidas sustitutas. Elaboramos modelos en VISSIM para recrear la operación del tráfico observada en campo y SSAM para determinar seis medidas sustitutas. Validamos la consistencia de los resultados por varios análisis estadísticos. El número de conflictos fue 72% menor en la turboglorieta. Mediante un análisis de conglomerados de las medidas sustitutas, los conflictos en la turboglorieta tienden a agruparse en un clúster, mientras que en la glorieta éstos están dispersos, sugiriendo una mejor organización de los flujos de tráfico en la turboglorieta. El análisis gráfico tridimensional de conglomerados y centroides permitió verificar que las medidas sustitutas indican una operación más segura en la turboglorieta, a pesar de presentar velocidades de aproximación más altas. Reduciendo la dimensionalidad, mediante análisis de componentes principales, la varianza acumulada de los dos primeros componentes (87.72%) permitió observar los resultados en dos dimensiones. Mediante análisis discriminante, respaldamos la clasificación de conflictos resultante de los clústeres. Los resultados validan la metodología y los beneficios en seguridad de la turboglorieta.

***Palabras clave*:** Análisis de componentes principales; Análisis de conglomerados; Análisis discriminante; Simulación de la seguridad vial; Vecino más lejano.

# 1. Introduction

## 1.1. Problem Statement

Historically, quantitative assessment of road safety has required crash occurrences in order to formulate engineering countermeasures and to develop predictive statistical models. With similar purposes, preventive and qualitative methods, such as Road Safety Audits (RSA), have been developed based on the perception of road safety; however, its subjectivity can be reflected in the evaluation, as stated by Koorey et al. (2003), Meister and Koorey (2003) and Cafiso et al. (2013). Given this situation, under a preventive and quantitative approach, different traffic conflict techniques have been developed to overcome the mentioned limitations up to some extent. According to Johnsson et al. (2018), the main techniques are the Swedish traffic conflict technique (Hydén, 1987), The Canadian conflict technique (Brown et al., 1984), The Dutch conflict technique (Kraay et al., 2013), and the American conflict technique (Parker and Zegeer, 1989). Each technique has variables that allow determining the severity level of a conflict, known as surrogate safety measures. This paper uses the variables of the American technique, which is explained below.

In accordance with Gettman and Head (2003), safety of traffic facilities is commonly assessed by tracking and analyzing police-reported motor vehicle crashes over time. Given that the nature of the crashes is both infrequent and random, this process is slow to reveal the need for remediation of either roadway design or flow-control strategy. This process is also not applicable to assess new designs that have yet to be built, or to assess new flow control strategies before being employed on-site. As an alternative to solve above restraints, microsimulation models are a useful tool. Therefore, using simulation of traffic conflicts, it is possible to estimate their surrogate safety measures by means of the Surrogate Safety Assessment Model, SSAM (Pu and Joshi, 2008).

Literature review allows identifying that surrogates as Time to Collision (TTC), Post-encroachment Time (PET), Initial Deceleration Rate (DR), Maximum deceleration rate (MaxD) and Maximum speed (MaxS), have been used in an univariate way, preferably, in accordance with Sayed and Zein (1999), Archer and Kosonen (2000), McDowell et al. (1983), Archer (2005) and Gettman et al. (2008), respectively. Given possible correlations between these variables, we consider that univariate assessments are not enough to conclude about road safety. Additionally, most relations between surrogates have not been explored yet (Tarko et al., 2009). Accordingly, assessments based on multivariate analysis of surrogates are needed to increase knowledge of traffic conflicts. Hence, this paper focuses on the comparative safety assessment of two types of roundabouts by multivariate methods.

## 1.2. Traffic Conflict and Surrogate Safety Measures

A traffic conflict is an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged (Bulla-Cruz and Lyons, 2020). This situation derives physical variables known as surrogate safety measures, used for determining the severity of the event. Figure 1 shows vehicular trajectories in a traffic conflict and six safety performance measures, that SSAM can report, defined as follows:

- Time to Collision minimum ($\mathrm{TTC}_{\mathrm{min}}$): minimum time in seconds required for two vehicles to collide if speeds and directions not change. It is a measure continuous with time; that is, the calculation may be performed at any instant within the sequence time frame (Hayward, 1972).
- Post-encroachment Time (PET): time in seconds between the first road user leaving the 'conflict zone' and the second one arriving at it (Laureshyn et al., 2017).
- Initial Deceleration Rate (DR): quantifies the magnitude of the deceleration action of a driver the moment he or she begins an evasive braking maneuver, in $\mathrm{m/s}^2$ (Johnsson et al., 2018).

- Maximum deceleration rate (MaxD): maximum deceleration of the through vehicle, in m/s$^2$ (Gettman et al., 2008).
- Maximum speed (MaxS): maximum of conflicting speeds of two vehicles involved in a conflict event, in m/s (Gettman and Head, 2003).
- Difference in vehicle speeds (DeltaS): absolute value of difference in conflicting speeds of two conflicting vehicles, in m/s (Gettman and Head, 2003).

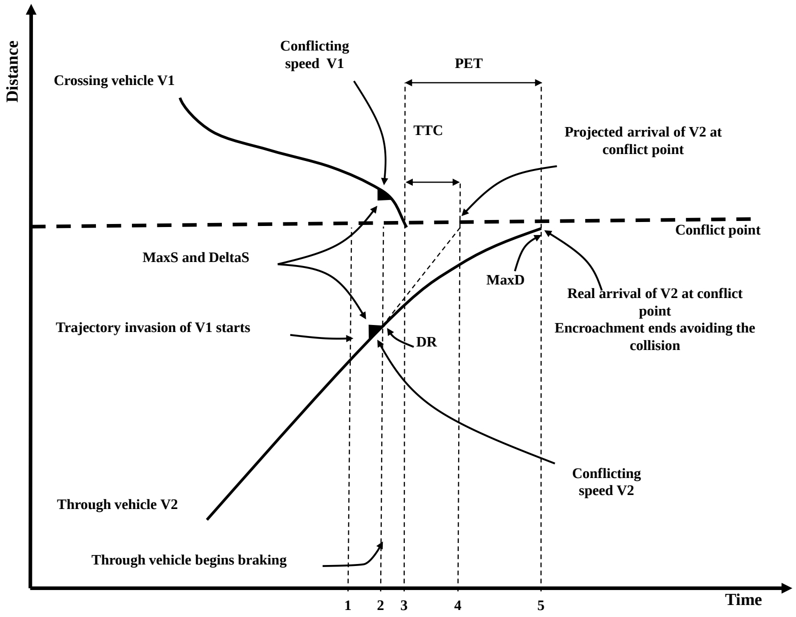


FIGURE 1: Vehicular trajectories in a traffic conflict and safety performance measures.

## 1.3. Roundabouts versus Turbo-Roundabouts

Fortuijn (2009) developed turbo-roundabouts as an attempt to deal with disadvantages related to higher driving speeds allowed by concentric two-lane roundabouts and the possibility of lane changing, which favor the occurrence of crashes. In accordance with Vasconcelos et al. (2014), a turbo-roundabout is a variation of conventional multilane roundabout in which spiral road markings and raised lane dividers force drivers to follow specific paths to their destination. This geometry eliminates weaving and cut-in conflicts by guiding drivers continuously from entrance to exit. The turbo-roundabout eliminates lateral conflicts due to its geometric configuration, reducing the total number of theoretical conflicts points from 16 at the two-lane roundabout to 10 at the turbo-roundabout. Figure 2 shows the location of conflict points at both types of roundabouts.

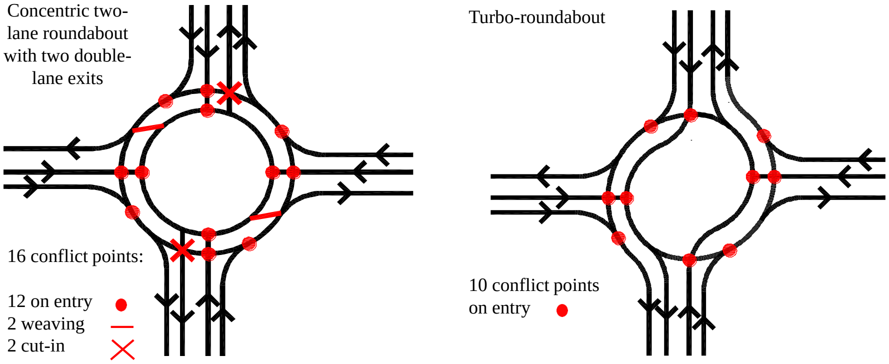


Figure 2: Theoretical location of conflict points.

## 1.4. Background Research

Road safety in roundabouts and turbo-roundabouts has previously been assessed through a Road Safety Audit (Bulla-Cruz and Castro, 2011), finding a 22% reduction in the overall risk in favor of turbo-roundabout. This audit compared geometric designs of proposed intersections.

Silva et al. (2014) found a reduction from 24 conflict points in a double-lane roundabout to 14 points in a basic turbo-roundabout, indicating an overall reduction in crash probability. Vasconcelos et al. (2014) used microsimulation models in AIMSUN and SSAM to compare different types of roundabouts, based on the number of conflicts, finding that the turbo-roundabout is the best option. Mauro et al. (2015) used a potential accident rate model for turbo-roundabouts, finding that these intersections provide: [*i*] reductions on the number of total potential accidents between 40% and 50%, and [*ii*] reductions on the number of potential accidents with injuries between 20% and 30%.

Hatami and Aghayan (2017) compared the traffic performance and efficiency of three types of roundabouts (modern, turbo and elliptical roundabouts), based on delay, capacity and geometrical features such as central island radius and different number of lanes. The authors also tested unsignalized and signalized controls in saturated and unsaturated flow conditions. They found that, in comparison with the turbo-roundabouts, the modern and the elliptical roundabouts showed the highest capacities with both unsignalized and signalized controls.

Campisi et al. (2018) performed a microsimulation study on the changes of the level of service and traffic safety outcomes based on surrogate safety measures, when connecting a turbo-roundabout with a BRT line, using VISSIM and SSAM as simulation tools, and $\mathrm{TTC}_{\mathrm{min}}$ and PET as surrogate indicators. They investigated six scenarios by varying directional traffic flows and their vehicle composition for evaluating the simulated safety outcomes.

Khasawneh and Alsaleh (2018) studied the possibility of upgrading at-grade roundabouts to turbo-roundabouts considering the Jordanian driving conditions, and how such upgrade could affect the selected performance measures: safety, capacity, queue length, delay, and level of service. The authors selected and analyzed three roundabouts using SIDRA software under off-peak and peak traffic conditions to estimate capacity, queue length, delay, and level of service under the existing design. Then they applied two different designs for each roundabout, using TORUS software, by changing some geometrical features, such as inner radius and opening width. Finally, they analyzed the designs, using VISSIM software, to assess the effect of implementing a turbo-roundabout instead the conventional roundabout. The findings show that the turbo-roundabouts offer higher capacities, lower delays and better level of service in comparison with the existing intersections. Furthermore, turbo-roundabouts present higher safety levels than typical roundabouts, by reducing conflict points from 32 at the typical roundabouts to only 12 at the proposed turbo-roundabouts.

Gallelli and Vaiana (2019) studied the safety improvements achieved when transforming a standard existing roundabout, with unbalanced flow distribution, into an egg turbo-roundabout, using VISSIM simulation software and then SSAM for traffic conflicts detection. The authors collected video-observed traffic information regarding speeds, critical gaps, queue lengths, and floating car data at an existing roundabout for its simulation in VISSIM, with its corresponding calibration. Then, they simulated the proposed turbo-roundabout using the previously calibrated parameters. As result, they compared the two roundabout scenarios based on the spatial distribution of the simulated traffic conflicts determined by SSAM, reporting a strong reduction in the total number of traffic conflicts (85%), particularly rear-end conflicts (95%). Finally, the authors state that “more reliable indications must be obtained in terms of safety measures, for example considering other kinds of intersections and specific safety parameters ($\text{TTC}_{\text{min}}$, PET, DR, etc.)”.

Balado et al. (2019) modeled a turbo-roundabout and a roundabout with Petri nets, which are both graphical and mathematical representations that allow a realistic modeling of urban systems. They used the results of the model to analyze and to compare the traffic safety through indicators of complexity at both intersections. The case study corresponds to a real-world transformation from roundabout to turbo-roundabout. Petri nets allowed confirming the complexity of the network at the roundabout, as well as the large number of maneuvers that a driver can do in it. The geometry of the turbo-roundabout causes the possibilities of movement to be reduced, limiting the options to the driver. The researchers modeled the main maneuvers causing accidents and presented their solutions in a turbo-roundabout. They conclude that the turbo-roundabout is safer, given the short displacements and that Petri nets are applicable to circular systems.

Elhassy et al. (2020) used VISSIM for determining the traffic implications of converting a high-volume multi-lane roundabout into a turbo-roundabout. They examined three different designs for comparing the two types of roundabouts. The authors proposed better designs of the roundabout, reflected in the improvement of the level of service. Their results showed that the capacity of the conventional three-lane roundabout was higher than the capacity of the turbo-roundabouts, concluding that turbo-roundabouts are not suitable for intersections with traffic volumes exceeding 4500 vehicles per hour.

Liu et al. (2020) evaluated the safety and traffic performance of turbo-roundabouts for a five-branch roundabout in Shanghai. The authors built VISSIM models for the roundabout and the proposed turbo-roundabout, performing several tests under diverse traffic volumes and central island radius. Subsequently, they analyzed the conflict statistics extracted from the trajectory files in SSAM, using $\mathrm{TTC}_{\mathrm{min}}$ and DeltaV as safety indicators and conflict frequency for safety performance evaluation. The findings remark that the turbo-roundabout could enhance the safety performance in most volume situations. The turbo-roundabout design presented a limitation regarding transportation effectiveness. High traffic volumes with large radius could cause important delays compared with no-channelized designs. Finally, the authors provided design and construction procedures when using the turbo-roundabout concept.

Based on the literature review, surrogate safety measures have traditionally been used with an univariate approach, which supports the hypothesis and the research problem that give rise to this paper and to the opportunity for exploring the performing and validity of multivariate analysis of such surrogate measures.

### 1.5. Hypothesis and Objective

Since, traditionally, surrogate measures of safety are used in an univariate way, our research hypothesis states that it is possible to determine which one is the safest intersection between a conventional roundabout and a turbo-roundabout, based on traffic conflicts and using simultaneously the six surrogate measures, defined above, by means of multivariate methods.

Therefore, the objective of this paper is to assess and to compare the traffic safety performance, of two types of roundabouts, using multivariate statistical techniques, such as clustering, principal components analysis (PCA) and discriminant analysis, under a preventive approach.

## 2. Methods

### 2.1. Study Site

The two-lane roundabout, we evaluated in this study, is located in the Colombia's capital, Bogotá (Figure 3 left). As Bulla-Cruz et al. (2020) stated, this roundabout is the traffic control mechanism between the 72I Avenue and 43A South Street (4°36'09.19"N 74°08'56.56"W), in a residential neighborhood of the city, with an estimated Average Daily Traffic (ADT) of 18,000 motor vehicles.

During the peak traffic operation hour, we collected on video and field the necessary data (i.e. geometry, traffic volumes, and speed) for modeling in VISSIM 5.3 software. Table 1 shows the peak hour mixed traffic volumes per roundabout entrance, per movement allowed. We entered the traffic volumes into the model in periods of 15 minutes, according to field information.

Table 1: Peak hour mixed traffic volumes per roundabout entrance.

| Entrance | Movement | Traffic volume (v/h) |
|---|---|---|
| North | Through | 47 |
| | Right | 44 |
| | Left | 37 |
| | U-turn | 0 |
| South | Through | 86 |
| | Right | 21 |
| | Left | 610 |
| | U-turn | 3 |
| West | Through | 776 |
| | Right | 404 |
| | Left | 12 |
| | U-turn | 4 |
| East | Through | 221 |
| | Right | 31 |
| | Left | 10 |
| | U-turn | 2 |

In VISSIM, the behavior of drivers at roundabout entrances is governed by the gap acceptance theory. Accordingly, we determined the critical gaps on video, as Table 2 shows.

Table 2: Peak hour mixed traffic volumes per roundabout entrance.

| Left lane of the main road accessing to | Critical gap (s) |
|---|---|
| Inner lane of the roundabout | 2.0 |
| Outer lane of the roundabout | 2.0 |
| Right lane of the main road accessing to | Critical gap (s) |
| Inner lane of the roundabout | 1.8 |
| Outer lane of the roundabout | 3.6 |
| Single lane of secondary road accessing to | Critical gap (s) |
| Inner lane of the roundabout | 2.0 |
| Outer lane of the roundabout | 2.0 |

The model also required the allocation of operating speeds and free-flow speed distributions at different sites of the roundabout, in order to generate a realistic simulation. The maximum and minimum values of these distributions are:

- Branches: max 60 (km/h) and min 25 (km/h).

- Roundabout ring: max 30 (km/h) and min 20 (km/h).
- Entrances: max 25 (km/h) and min 15 (km/h).

On the other hand, given that the turbo-roundabout is a virtual proposal and that, to date, there is not one of these intersections in full operation in Bogotá, it was necessary to use critical gaps reported by Fortuijn (2009), for existing turbo-roundabouts in The Netherlands, as follows:

- Left lane of the main road: 3.37 s.
- Right lane of the main road: 3.67 s.
- Left lane of the secondary road: 3.07 s.

Based on traffic volumes and the available space, Figure 3 (right) shows the top view of the proposed turbo-roundabout design. Given this design, we adopted the desired operating speeds according to the radius of curvature of the different geometric elements of the road, in accordance with the design guidelines presented by Ministerio de Transporte - INVÍAS (2008).

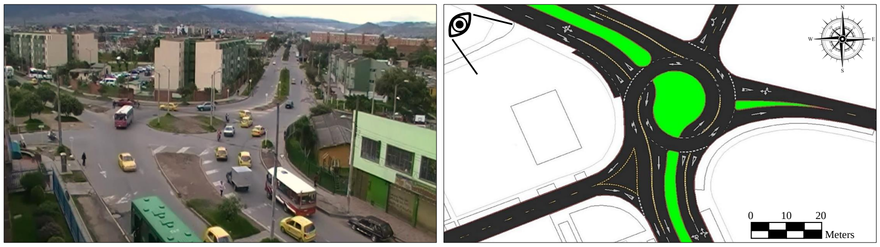


Figure 3: Study site (left) and proposed turbo-roundabout design (right).

With the purpose of evaluating the road safety of the roundabout from traffic conflicts, field information included empirical count of conflicts, without assessing their severity. As we define above, the traffic conflict is an event in which two road users approach each other in space and time, with collision course, to such an extent that there is a risk of collision if their movements remain unchanged. The empirical count consisted on identifying and counting such events, observing repeatedly the intersection operation videos, during the peak hour. Laureshyn and Varhelyi (2018) present the specific guidelines on conflict observation and identification.

## 2.2. VISSIM Simulation Models

The simulation models are fed with the information described above. Additionally, VISSIM is based on a psycho-physical perception driving behavior model composed by several parameters, known as Wiedemann 74 model (PTV AG, 2012), which defines the vehicular behavior (i.e., following, lane change and lateral), allowing the breaking of the lane discipline and simulating the filtering of motorcycles between other vehicles, as it happens in Bogotá. We kept most of the parameters at their default values. However, we modified two of them, according to field measurements, since we considered them essential to achieve a good simulation:

- Average standstill distance: is the average distance in standstill or waiting condition between consecutive vehicles. The field-observed value of this parameter was 0.7 m.
- Speeds for the definition of the queue condition: we assumed that a vehicle enters the queue condition when its speed is less than 8 km/h and leaves the condition at 4 km/h, once it starts to accelerate.

The simulation model needs to be validated by comparing the magnitudes of different traffic parameters, field-observed against simulated. In case the validation is not achieved, it is necessary to calibrate parameters of the model and verify the validation again, in an iterative process, as presented in the following sections. Based on the above input information, Figure 4 (left) shows the simulated roundabout; once we validated this model, we modeled the turbo-roundabout under the validated VISSIM environment. Therefore, Figure 4 (right) shows the simulated turbo-roundabout.

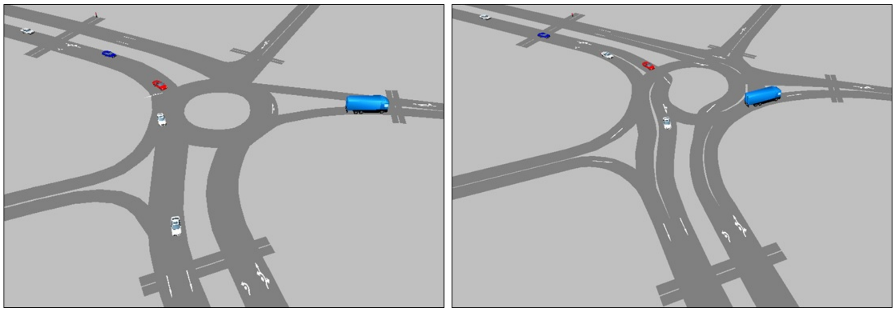


Figure 4: Microsimulation in the current situation (left) and proposed turbo-roundabout (right)

## 2.3. Surrogate Safety Assessment Model - SSAM

The Federal Highway Administration (Gettman et al., 2008), reported that SSAM and its validation "resulted in the development of a software tool that derives surrogate safety measures for traffic facilities from data output by traffic simulation models. By comparing simulation design cases, SSAM allows analysts to statistically judge relative safety of designs. An open-standard vehicle trajectory data format was designed; support for this format is added as an output option by four simulation model vendors/developers: PTV (VISSIM), TSS (AIMSUN), Quadstone (Paramics), Rioux Engineering (TEXAS)" and, recently, the Enhanced

Transportation Flow Open Source Microscopic Model (ETFOMM). Besides, in SSAM, conflict type is defined by the conflict angle between the trajectories of two road users (Zhou et al., 2011). Conflict types are: rear-end (0° - 45°), crossing (45° - 135°) and head-on (135° - 180°). Figure 5 shows the process for obtaining surrogate safety measures, using VISSIM and SSAM, which includes: [*i*] the construction of the VISSIM model based on field data, [*ii*] the calibration of the model by modifying VISSIM parameters, [*iii*] the validation of the model by comparing video-observed traffic parameters against simulated traffic parameters (i.g., traffic volumes, queue length, delay), [*iv*] once the model is validated, the trajectory files are extracted to be processed in SSAM, [*v*] the model validation based on the comparison between the number of video-observed traffic conflicts and the number of simulated traffic conflicts, and [*vi*] once the model is valid, by both traffic and conflicts, the surrogate safety measures for the simulated conflicts, reported by SSAM, are considered valid. By default, SSAM presents a $\text{TTC}_{\text{min}} \leq 1.5$ s, which can be assumed to filter out serious conflicts when there is no field conflicts count but —when there is a count as in this study— it is necessary to calibrate $\text{TTC}_{\text{min}}$ for eliminating such an assumption. The above supports the methodological approach of this study, which presents the following section.

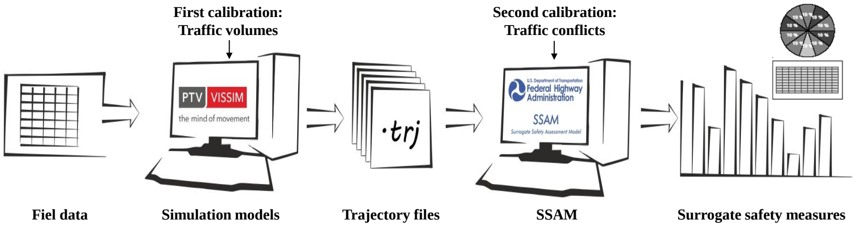


FIGURE 5: The VISSIM and SSAM process, adapted from Gettman et al. (2008).

## 2.4. Methodological Approach

For the proposed evaluation, we followed the steps of Figure 6 to obtain the traffic conflicts and their surrogate safety measures for both intersections —based on the method proposed by Huang et al. (2013)— using VISSIM and SSAM.

Methodological development included the following steps: [*i*] in VISSIM, we successfully validated a microsimulation model of the two-lane roundabout by comparing average values of different observed and simulated traffic indicators; we used the Wiedemann 74 car-following model due to the urban setting of the study site; once traffic demand for the roundabout was known, we designed and simulated a proposed basic turbo-roundabout under the previous calibrated VISSIM environment, [*ii*] we extracted the vehicular trajectory files from validated simulation models which we analyzed using SSAM to obtain the amount and type of traffic conflicts and their surrogate measures; the evaluation required the calibration process described in Section 3, finally, [*iii*] we statistically analyzed the traffic conflicts and surrogate measures by means of cluster, principal component and discriminant analysis to compare the two intersections in terms of traffic safety.

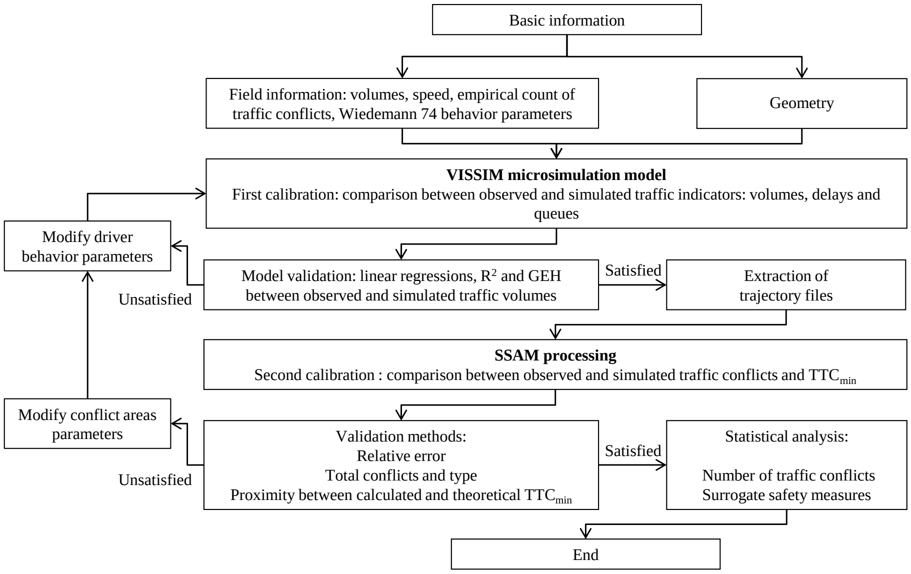


Figure 6: Methodological approach.

## 2.5. Clustering Analysis, PCA and Discriminant Analysis

Everitt et al. (2011) stated that “cluster analysis and other multivariate analysis techniques are now often called data mining”. Clustering analysis is a way to summarize large databases and grouping events (i.e. traffic conflicts in this paper, and variables or surrogate measures of safety, that indicate their severity) to identify, in analogy to medicine sciences, which treatment —roundabout type— is the best solution against a disease —traffic crashes. According to Pardo and del Campo (2007), in this research the formation of clusters is synonymous with classification, since it seeks to classify each traffic conflict in a certain type of roundabout, according to its severity.

Although cluster analysis can provide a good approximation to the solution of the problem, it is interesting to verify whether it is possible to reduce the size of the database without losing interpretation of the results. The PCA allows obtaining such reduction and interpreting data (Washington et al., 2011). Sánchez et al. (2008) state that the PCA is a data representation technique focused on the reduction of dimension. After dimensional reduction, the obtained Discriminant function analysis (DFA) lets the classification of unknown individuals —traffic conflicts— and the probability of their classification into a certain group, such as roundabout type (Moore, 2013). The discriminant analysis divides the sample space into sub-spaces by means of hyper-planes that allow estimating the best possible separation of the groups under study (Barajas and Morales, 2009).

# 3. Results and Discussion

## 3.1. Model Calibration by Traffic and Conflicts

According to the stages raised in the methodology, we built the microsimulation model of the existing roundabout. Afterwards, we ran ten random runs of the model and we compared the mean values of the simulated traffic parameters against the field values using linear regressions for calibrating and validating the model. Maximum observed queue length per approach presented a $R^2 = 0.97$, while the average delay per approach presented a $R^2 = 0.64$. The GEH Statistic $= 0.56$ was calculated for sum of all link traffic flows, comparing observed and simulated volumes, a GEH$<$ 4 indicates a successful calibration, in accordance with Dowling et al. (2004).

We adopted the process proposed by Huang et al. (2013) to calibrate the model in terms of conflicts. A well-tuned model returns low relative error, when comparing the number of simulated conflicts against observed conflicts, indicating the achievement of a good calibration. However, this calibration is complex because the number of field conflicts depends on observer's perception. Moreover, $\mathrm{TTC}_{\mathrm{min}}$, related to the consideration of when a conflict ceases to be mild and becomes serious, may vary according to such individual perception, being 1.5 s the most accepted value proposed by Hydén (1987).

We used the variation of $\mathrm{TTC}_{\mathrm{min}}$ to calibrate SSAM by comparing the amount of observed and simulated conflicts, estimating the $\mathrm{TTC}_{\mathrm{min}}$ value that produces the lowest relative error between quantities. The purpose is to verify how close local $\mathrm{TTC}_{\mathrm{min}}$ is to $\mathrm{TTC}_{\mathrm{min}} = 1.5$ s. Figure 7 shows that a $\mathrm{TTC}_{\mathrm{min}} = 1.37$ s produces a relative error of 4.46% between the total of observed and simulated conflicts; this $\mathrm{TTC}_{\mathrm{min}}$ satisfies both rear-end and crossing conflicts and the total that corresponds to their sum. In this respect, some authors reported the local $\mathrm{TTC}_{\mathrm{min}}$ of their investigations: Torres et al. (2010), 1.4 s at suburban priority T-type intersections in Santiago (Chile) and Huang et al. (2013), 1.6 s at signalized intersections in Nanjing (China). In this study, we noticed that observers paid more attention to most severe conflicts, not considering all the serious events. Since aggressive driver behavior is common at Bogotá's roundabouts. The above statement explains a $\mathrm{TTC}_{\mathrm{min}}$ lower than those reported in other countries. We clarified that there were no conflicts with pedestrians or cyclists. Once we calibrated the base model, we built the turbo-roundabout model under the previously calibrated VISSIM environment, adapting the geometric design to available space.

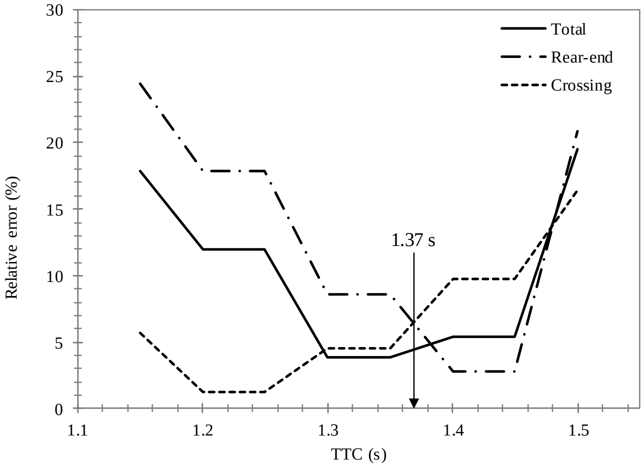


FIGURE 7: Relative error between field and simulated conflicts based on $\mathrm{TTC}_{\min}$.

## 3.2. Comparative Assessment Based on Number of Conflicts

Based on calibrated $\mathrm{TTC}_{\min} = 1.37$ s, we obtained the number of serious conflicts at the roundabout and at the turbo-roundabout (see Table 3). The total number of conflicts at the roundabout was 338, which corresponds to 209 (rear-end) and 129 (crossing). At the turbo-roundabout, the total was 96, corresponding to 44 (rear-end) and 52 (crossing). The above quantities and their difference, by conflict type, translate into a percentage change in favor of the turbo-roundabout, of -72%, -79% and -60%, respectively. These results are congruent with Vasconcelos et al. (2014), that found a total of 329 conflicts at the roundabout and 92 at the turbo-roundabout, implying a 72% reduction, too. Likewise, this decreasing is consistent with the benefits, in terms of crashes reduction (80%), at intersections regulated by roundabouts and replaced by turbo-roundabouts, in The Netherlands (Fortuijn, 2009).

TABLE 3: Comparison between intersections based on the number of conflicts.

| Parameter | Total | Rear-end | Crossing |
|---|---|---|---|
| Angle Threshold | - | 0° - 45° | 45° - 135° |
| Roundabout | 338 | 209 | 129 |
| Turbo-roundabout | 96 | 44 | 52 |
| Difference | 242 | 165 | 77 |
| Change | -72% | -79% | -60% |

Figure 8 shows the location of simulated conflicts generated by SSAM for a total of ten model runs, with a $\mathrm{TTC}_{\min}$ of 1.37 s. As shown, density of crossing conflicts (blue squares) and rear-end conflicts (yellow circles) is lower at the turbo-roundabout. Concentration of events allows observing specific conflict areas. This model highlights the elimination of conflicts in a large part of the roundabout ring, improving road safety and inducing road users to a safer driving behavior.

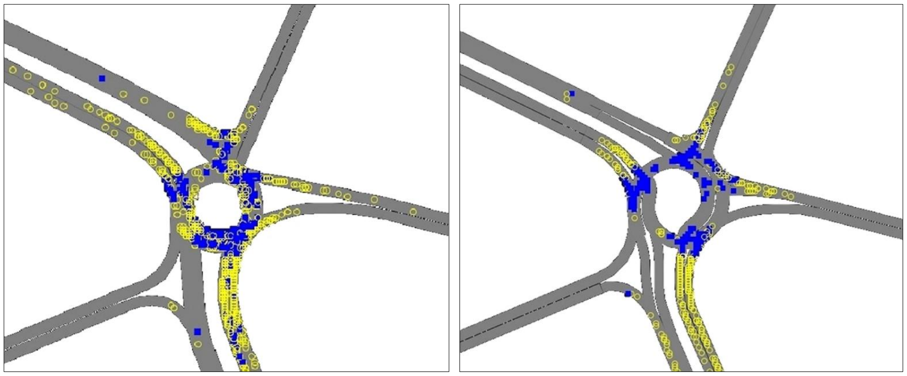


FIGURE 8: Location of simulated conflicts at existing roundabout (left) and at proposed turbo-roundabout (right).

### 3.3. Statistical Analysis for Surrogate Measures Validation

We obtained six surrogate measures of safety, from models in VISSIM and SSAM, for each traffic conflict simulated. We performed several regression models between pairs of surrogate measures with the aim of verifying the consistency of the values obtained and validating both simulation models and surrogate measures. Figure 9 to Figure 12 show the polynomial regression models that presented the best fit.

Figure 9 shows the polynomial regression between $\text{TTC}_{\text{min}}$ and PET for the roundabout and the turbo-roundabout. In both roundabouts the tendency is valid, according to the theory, given that when $\text{TTC}_{\text{min}}$ increases PET also does, being $\text{PET} \geq \text{TTC}_{\text{min}}$ in the vast majority of cases. Figure 9 also presents the confidence interval (95%) of the regression model (green area) and the prediction interval (yellow area).

The continuous line has slope = 1, which means a 1:1 ratio between the two variables. The dots below this line correspond to conflicts in which there was acceleration rather than deceleration to avoid conflict. These conflicts do not match with the American conflict technique, in which deceleration is part of evasive action. Despite the above, we maintained such conflicts within the evaluation to incorporate atypical situations generated by simulation models. In this case, acceleration maneuvers are justified due to aggressiveness considered in the model to achieve its validation.

Figure 10 presents the polynomial regression between $\text{TTC}_{\text{min}}$ and MaxS. At both roundabouts, we observed that the higher the $\text{TTC}_{\text{min}}$ the smaller is MaxS. As is to be expected, when traveling at a low speed the $\text{TTC}_{\text{min}}$ presents safer values in most conflicts. At the roundabout, there is a notoriously greater number of conflicts with $\text{TTC}_{\text{min}} \approx 0$ than at the turbo-roundabout. Despite this difference, at the turbo-roundabout these conflicts occurred at higher speeds, given elimination of lateral conflicts due to geometry. In general, $\text{TTC}_{\text{min}}$ and MaxS present safer values at the turbo-roundabout.

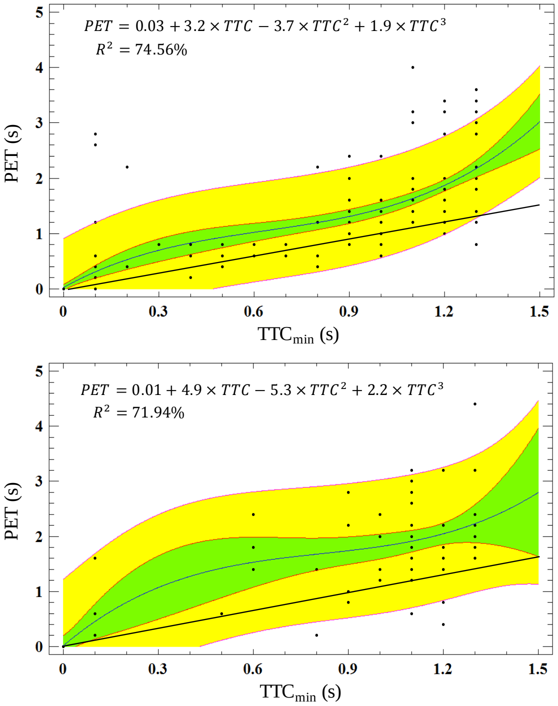


Figure 9: TTC$_{\min}$ vs. PET at roundabout (up) and at turbo-roundabout (down).

Figure 11 shows that, at the roundabout, there are more conflicts with positive DR than at the turbo-roundabout and these conflicts have a TTC$_{\min} \approx 0$. This is evidence of aggressive driving behavior generated for model validation, as well as virtual crashes with TTC$_{\min} = 0$ that VISSIM generates due to simulation errors of this software, which is constantly improving. In general, at both intersections, it is necessary a more negative DR to achieve a safe TTC$_{\min}$, consequently linked with MaxS.

Figure 12 presents the relationship between TTC$_{\min}$ and conflict angle. At both intersections, we observed that for low conflict angle values, TTC$_{\min}$ values are higher. Therefore, the smaller the conflict angle the safer is the conflict. This tendency is more evident at the turbo-roundabout because it let a smaller angular threshold with safer TTC$_{\min}$.

Table 4 and Figure 13 show the univariate statistical analysis of data. TTC$_{\min}$ and PET indicate a safer operation at the turbo-roundabout. However, MaxS and DeltaS indicate that conflicting speeds are higher at the turbo-roundabout and, due to this, the variables related to deceleration, DR and MaxS, are more negative. Accordingly, Figure 13 shows Pearson's correlation matrices of surrogate safety measures for both roundabouts. The high correlations between variables indicated the needing of the application of multivariate statistical techniques to study the problem. We used **RStudio**, and the **corrplot** (Wei et al., 2017) and **psych** (Revelle, 2018) packages in this analysis.

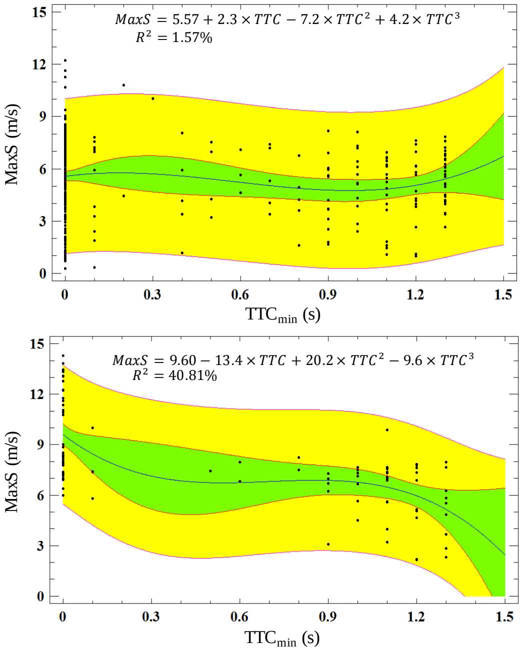


FIGURE 10: TTC$_{\text{min}}$ vs. MaxS at roundabout (up) and at turbo-roundabout (down).

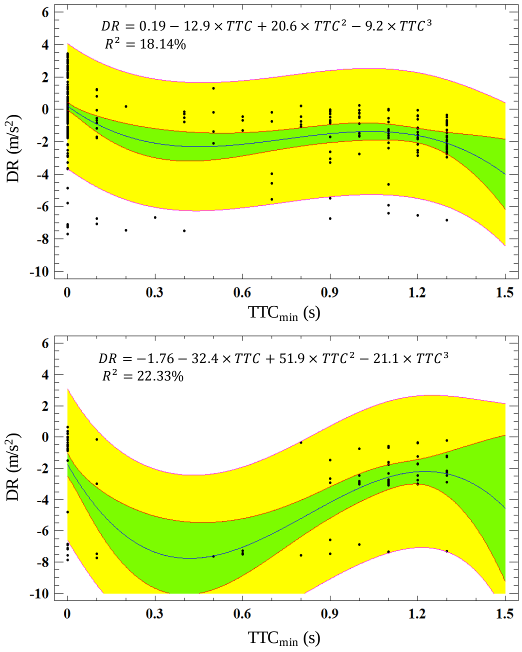


FIGURE 11: TTC$_{\text{min}}$ vs. DR at roundabout (up) and at turbo-roundabout (down).

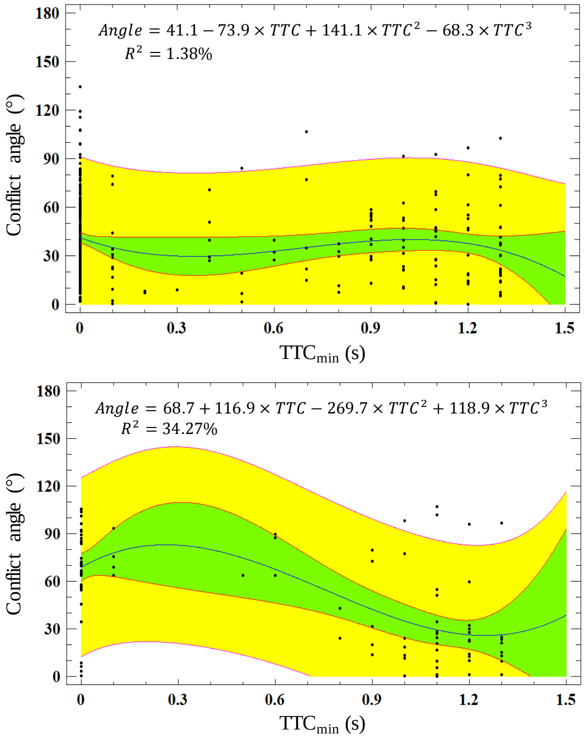


FIGURE 12: $\text{TTC}_{\text{min}}$ vs. Conflict angle at roundabout (up) and at turbo-roundabout (down).

TABLE 4: Descriptive statistics.

| Parameter | $\text{TTC}_{\text{min}}$ (s) | PET (s) | MaxS (m/s) | DeltaS (m/s) | DR (m/s$^2$) | MaxD (m/s$^2$) |
|---|---|---|---|---|---|---|
| Roundabout | | | | | | |
| Mean | 0.32 | 0.53 | 5.42 | 3.78 | -0.46 | -1.11 |
| Standard Deviation | 0.49 | 0.89 | 2.27 | 2.16 | 2.16 | 2.67 |
| Turbo-roundabout | | | | | | |
| Mean | 0.61 | 1.10 | 7.68 | 7.19 | -2.64 | -2.91 |
| Standard Deviation | 0.55 | 1.12 | 2.63 | 2.61 | 2.69 | 2.65 |

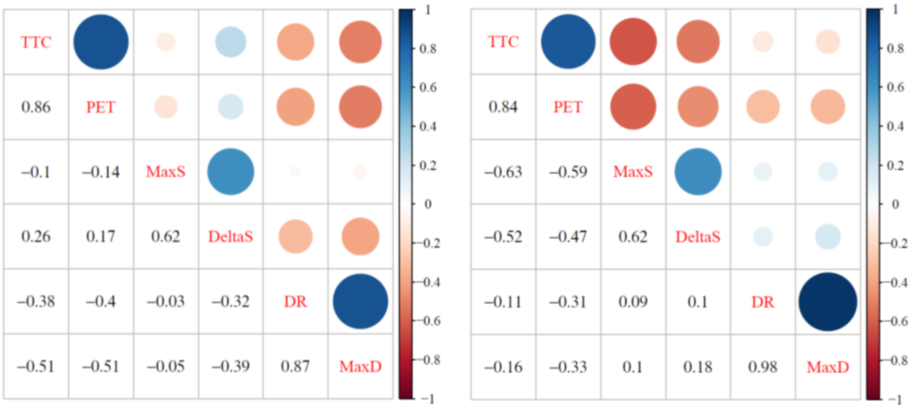


FIGURE 13: Pearson's correlations matrices of Surrogate measures, roundabout (left) and turbo-roundabout (right).

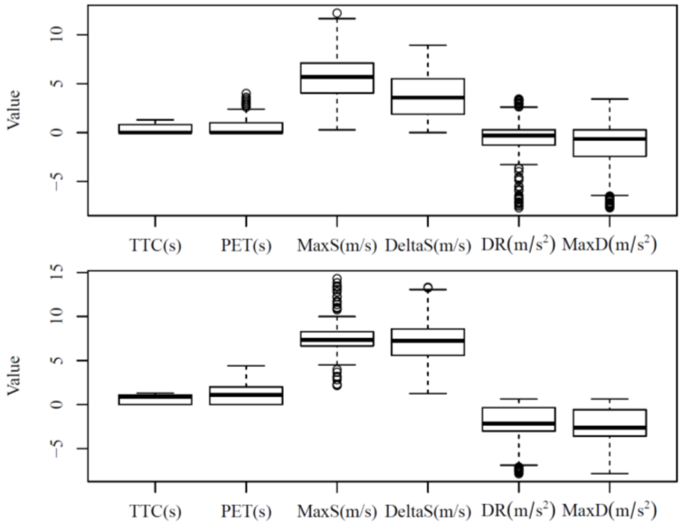


FIGURE 14: Boxplots of surrogate measures, roundabout (up) and turbo-roundabout (down).

## 3.4. Complete-Linkage Clustering Analysis

In accordance with Johnson and Wichern (2007), we tested different hierarchical clustering methods and assigning distances, under conditions of standardization and non-standardization of variables. We evidenced that a better interpretation of the clusters is obtained when the variables are not standardized; this is because all variables are time-based. In this regard, Milligan and Cooper (1988) state that "deciding on a suitable form of standardization of variables can improve recovery of the true cluster structure, but it is only one of several decisions faced by the applied researcher".

Based on the before-mentioned, we discussed a complete-linkage clustering analysis and Euclidean distance. This analysis produced the cluster structure that better explain the relationship between variables and type of roundabout. In accordance with Punj and Stewart (1983), this method is also known as furthest neighbor cluster analysis, in which "an observation is joined to a cluster if it has a certain level of similarity with all current members of the cluster". We carried out the analysis using **RStudio** and the **dendextend** package (Galili, 2015).

As shown in Figure 15, a first cluster analysis with original variables allowed noticing that conflicts at the turbo-roundabout (green labels) tend to group in a single cluster (cluster 2) due to their association with a pattern of driving behavior induced by road geometry. On the other hand, at the roundabout (cluster 1) there is greater dispersion because conflicts (red labels) can occur in different ways at different points of the intersection. At the roundabout, it is not possible to control or concentrate conflict points in specific locations as effectively as at the turbo-roundabout.

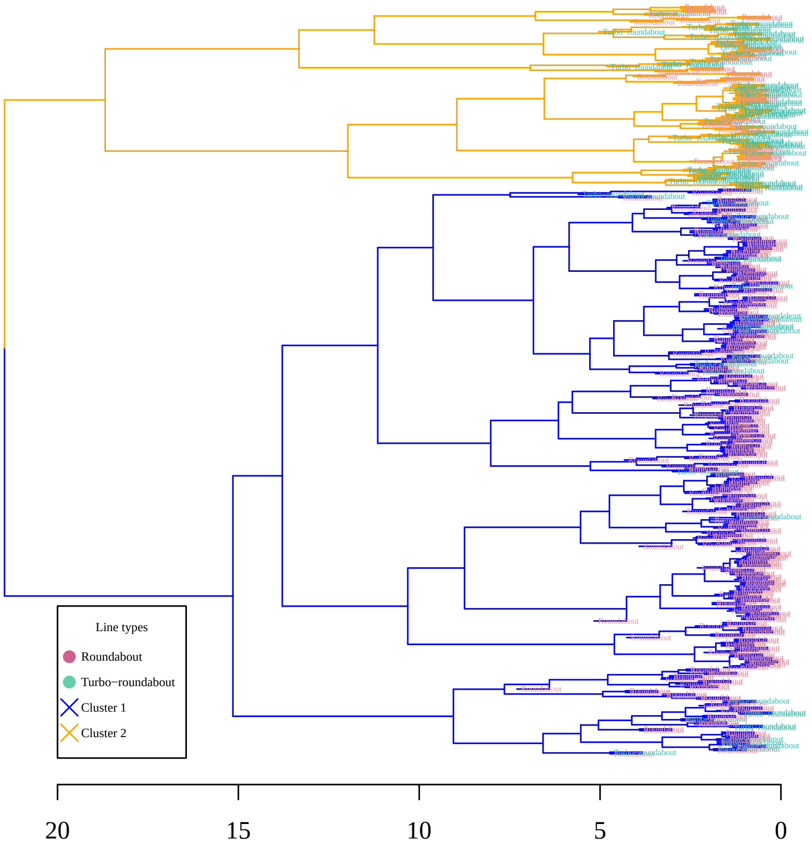


FIGURE 15: Dendrogram of complete-linkage clustering analysis with original data.

Figure 16 (left) shows a three-dimensional graphic relating $\text{TTC}_{\text{min}}$, PET and MaxS. Clouds of dots correspond to conflicts of cluster 1 (blue dots) and cluster 2 (red dots). As mentioned above, conflicts of the turbo-roundabout belong to cluster 2. Three-dimensional graphical analysis of clusters allowed verifying that surrogate measures indicate safer operation at the turbo-roundabout. Nevertheless, some conflicts in this intersection showed high values of MaxS, as it was also observed in Figure 10.

Figure 16 (right) shows a three-dimensional graph relating DR, MaxD and DeltaS. In general, cluster 1 provided evidence of aggressive driving behavior at the roundabout, given the important number of conflicts with positive DR and MaxD. In the same sense, cluster 2 indicated most negative decelerations at the turbo-roundabout, which agrees with high values of MaxS before-mentioned. DeltaS indicates that most of conflicts at the roundabout had safer speed differences between pairs of vehicles. Based on these results, we found that approaching speeds were higher at the turbo-roundabout and that a greater deceleration was necessary to avoid collisions, which leads to $\text{TTC}_{\text{min}}$ and PET safer.

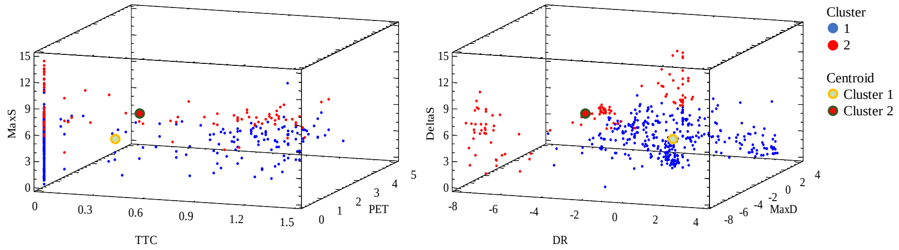


FIGURE 16: Scatter plot of $\text{TTC}_{\text{min}}$, PET and MaxS (left) and DR, MaxD and DeltaS (right).

Table 5 presents the location coordinates of clusters' centroids. Based on centroid of cluster 1, the roundabout has $\text{TTC}_{\text{min}}$ and PET values closer to zero, indicating riskier operation compared to turbo-roundabout operation. In addition, centroids show that MaxS and DeltaS presented safer values at the roundabout and indicate that DeltaS does indeed have safer values at the roundabout, as observed in the clusters. Regarding DR and MaxD, decelerations were higher at the turbo-roundabout, given the higher approaching speeds to the conflict point. Such decelerations allowed obtaining safer $\text{TTC}_{\text{min}}$ and PET.

TABLE 5: Location of clusters' centroids.

| Cluster | $\text{TTC}_{\text{min}}$ (s) | PET (s) | MaxS (m/s) | DeltaS (m/s) | DR ($\text{m/s}^2$) | MaxD ($\text{m/s}^2$) |
|---|---|---|---|---|---|---|
| 1 | 0.32 | 0.53 | 5.42 | 3.78 | -0.46 | -1.11 |
| 2 | 0.61 | 1.10 | 7.68 | 7.19 | -2.64 | -2.91 |

## 3.5. Principal Components Analysis

To observe the six variables simultaneously, we reduced the problem dimensionality using a PCA. We carried out the analysis using **RStudio** and the **stats** package (R Core Team and contributors Worldwide, 2019). The cumulative variance of the first two components was 87.72%, suggesting that is advisable to use the first two components with low loss of information. This is also validated by the eigenvalues of first (15.80), second (9.09) and third components (1.98), which is consistent with the procedure suggested by Pérez et al. (2006).

Table 6 and Figure 17 show the loadings of variables into the first two principal components. These values allowed calculating new variables detailed below. We observed that variables related to deceleration and speed have greatest load in the first principal component (Prin1), with an important load of time. On the other hand, in second principal component (Prin2), variables related to speed and deceleration have greatest load, also with an important load of time. The resulting loads allowed naming the new variables as DST and SDT, respectively.

Table 6: Components' cumulative variance, loadings and new variables.

| Component | $R^2$ | $TTC_{min}$ | PET | MaxS | DeltaS | DR | MaxD | New variable |
|---|---|---|---|---|---|---|---|---|
| Prin1 | 55.67% | 0.047 | 0.093 | 0.332 | 0.495 | -0.527 | -0.597 | DST |
| Prin2 | 87.72% | -0.057 | -0.130 | 0.644 | 0.500 | 0.361 | 0.430 | SDT |

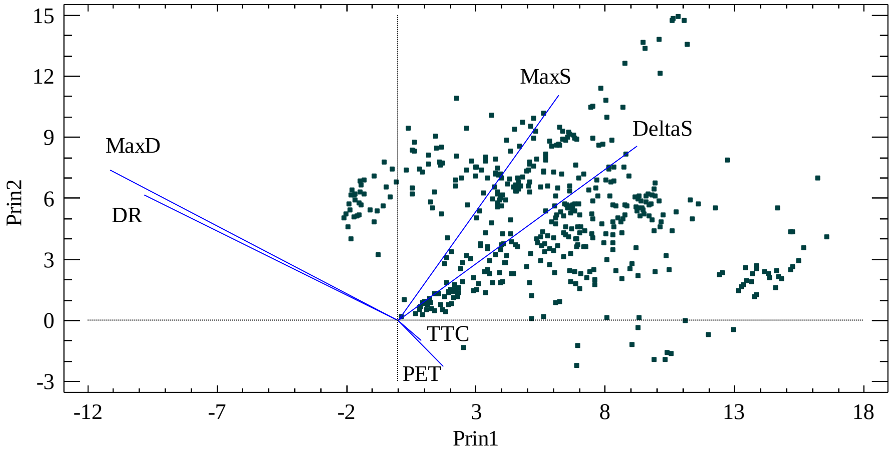


Figure 17: Graphical representation of component loadings.

We developed a new cluster analysis once extracted the first two principal components. The dendrogram in Figure 18 confirmed that most of conflicts at the turbo-roundabout belong to cluster 2, as we indicated in Figure 15, revealing low loss of information when classifying conflicts based on new variables DST and SDT.

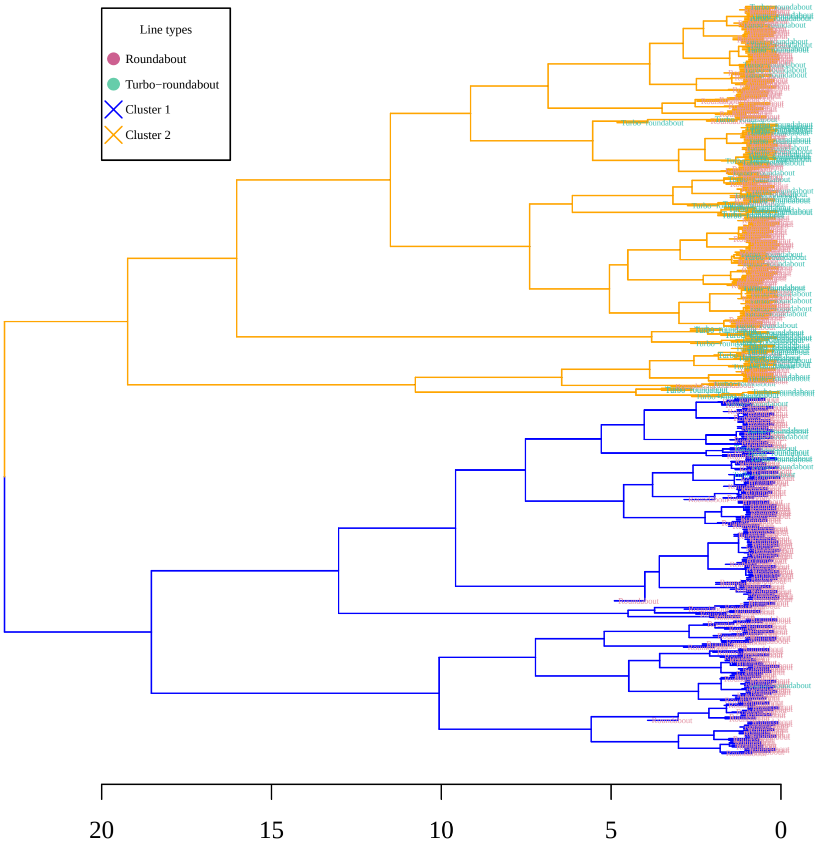
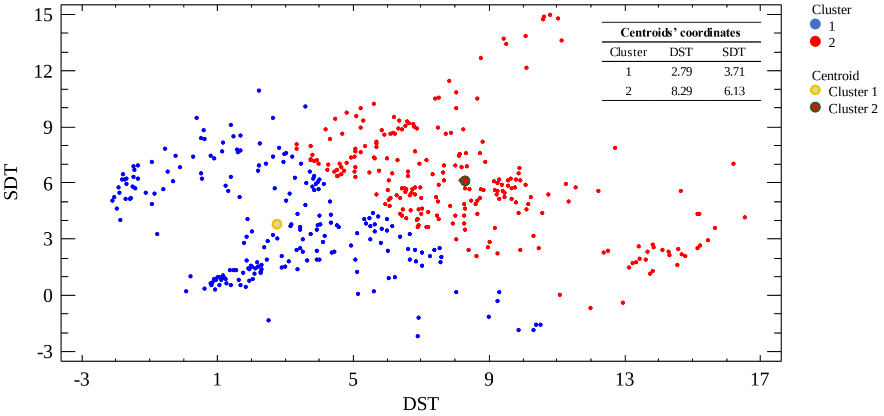


Figure 18: Dendrogram of cluster analysis of first two principal components.

Figure 19 shows a new scatter plot for DST and SDT. We used centroids to compare the two intersections given data dispersion, considering that conflicts of the turbo-roundabout belong to cluster 2. Variables related to time presented safer values for the turbo-roundabout, while deceleration and speed variables presented safer values for the roundabout, as stated in the first cluster analysis.

According to McDowell et al. (1983), Sayed and Zein (1999), Archer and Kosonen (2000), Archer (2005), Gettman et al. (2008) and Habtemichael and De Picado Santos (2014), high values of surrogate safety measures related to speed and deceleration (highly negative) indicate high severity levels of expected crashes, as opposed to variables related to time. The foregoing validates the findings on road safety performance for the two types of roundabouts.



| **Centroids' coordinates** | | |
|---|---|---|
| Cluster | DST | SDT |
| 1 | 2.79 | 3.71 |
| 2 | 8.29 | 6.13 |

Figure 19: Scatter plot with new variables DST and SDT.

## 3.6. Discriminant Function Analysis

Scatter plot in Figure 19 allowed observing that exists a linear separation between clusters. We developed a discriminant function analysis to verify and describe if there are significant differences between the clusters. In addition, from such discriminant function we established a linear combination that allows classifying new traffic conflicts. The discriminant function obtained, Equation 1, was statistically significant ($p$-value $= 0.00001$), with a confidence level of 95% and a 98.56% of correctly classified cases, where $D$ is the discriminant score for each observation classification. The discriminant function is the linear combination of the $p$ variables that form the data set such that the distance between the two groups of vectors of means is maximized (López, 2011).

$$D = -3.03504 + 0.652558 \cdot DST + 0.771818 \cdot SDT \tag{1}$$

In the first cluster analysis, 67% of the conflicts at the turbo-roundabout belonged to cluster 2 while, in the second cluster analysis, 88% of the conflicts belonged to cluster 2. This means that we achieved a better classification of conflicts using the first two principal components in the second cluster analysis. After the above, we used the first two principal components for obtaining the discriminant linear function, that achieved a 98.56% of correctly classified cases. We consider that the high percentage of cases classified correctly by the discriminant function is due to the good classification achieved in the second cluster analysis using the first two principal components, validating the statistical approach proposed.

# 4. Conclusions

We developed a case study to validate the use of microsimulation of traffic conflicts and multivariate assessment of surrogate safety measures. We obtained surrogate measures of safety from VISSIM models and SSAM for evaluating and comparing road safety performance of two different roundabouts types. We estimated a critical $\text{TTC}_{\text{min}} = 1.37$ s; to date there are no previous references for measuring this parameter in Bogotá city. We consider that more local research is needed to calibrate the different parameters for using the conflicts technique correctly. Based on the critical $\text{TTC}_{\text{min}}$, the turbo-roundabout presented a total number of conflicts 72% lower than the roundabout, confirming safety benefits of this novel design.

Polynomial regressions allowed verifying the validity and consistency of the surrogate measures obtained, even in conditions of aggressive driver behavior. Results obtained through univariate analysis, linear regressions and multivariate cluster analysis are consistent for comparing such surrogate measures. In general, we observed safer operation at the turbo-roundabout than at the roundabout, but the former registered higher speeds of approach to conflict point, as we confirmed by the statistical analysis presented.

Multivariate analysis of surrogate measures proved to be a helpful tool for comparing different intersection alternatives, in terms of road safety. In order to facilitate the interpretation, it is possible to reduce the number of variables using PCA without relevant loss of information. The cumulative variance of the first two components was 87.72%, suggesting that is advisable to use the first two components with low loss of information. This is also validated by the eigenvalues of first (15.80), second (9.09) and third components (1.98). Moreover, we reached similar conclusions about safety when working with the original units of the surrogate measures. These multivariate statistical techniques allow recognizing the severity of the events at each type of intersection based on surrogate measures. The dendrogram in Figure 18 confirmed that most of conflicts at the turbo-roundabout belong to cluster 2, as we indicated in Figure 15, revealing low loss of information when classifying conflicts based on new variables DST and SDT. Through the developed methodology it is possible to estimate the influence of different traffic control mechanisms and their relationship with the users' behavior.

Scope of traffic simulation on the study of road safety is broad. Regarding the evaluated intersections, this research concludes that it is necessary to conduct studies at different periods of the day, both in vehicular congestion and low demand conditions. The above is suggested to enlarge the field of analysis and knowledge of traffic conflicts. Likewise, it is necessary to investigate the interaction between pedestrian, bicycle, vehicle and infrastructure using traffic conflicts and surrogate safety measures, based on simulation models and multivariate statistical methods. It is equally important to clarify that there are tools for the analysis of trajectories of road users on video, in development, which allow estimating the severity of field conflicts. We are currently entering this field with the purpose of improving the accuracy of our models in VISSIM.

## Acknowledgements

The authors thank to the Universidad Nacional de Colombia and the Administrative Department of Science, Technology and Innovation of Colombia (Colciencias) in the call 617/2013, for their support during the performing of this research.

[Received: September 2019 — Accepted: December 2020]

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