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The role of perceptions in pedestrian quality of service

Dissertation

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Executive summary

There are many types of pedestrian performance or service indicators (PPSI) that have been applied worldwide to evaluate the service provided to pedestrians by urban sidewalks, such as the pedestrian level of service (PLOS) or the quality of service (QoS). Different inputs have also been used to explain the PPSI considering three groups of attributes: objective attributes, expert judgement, and the flow-capacity relation. In this thesis, it was identified variety of predictors (environmental, sociodemographic, physical, and perceptual) that can potentially be used to explain PPSI.

However, the literature suggests that the methodologies tend to be site dependent (Hasan, Siddique, Hadiuzzaman, & Musabbir, 2015) and there are not many studies that compare their forecasting potential. Similarly, when considering predictors (environmental, sociodemographic, physical, and perceptual), there are not many studies that quantify the pure and joint effects of each group on the variance explanation of the perceived QoS. In addition, to explain the way that pedestrians perceive the PPSI considering the interactions they have when walking, a structural equation model (SEM) was developed by Geetha Rajendran Bivina & Parida (2019), where some latent variables positive effects on the PLOS are explained.

For this reason, the aims of this thesis were: firstly, to test the forecasting performance of some methodologies identified to calculate the PPSI considering the categories of different inputs (flow-capacity relation, objective data, and perceptual information). Secondly, to analyze their applicability to Bogotá's local context. Thirdly, to analyze the individual and joint effect of the different groups of predictors (environmental, sociodemographic, physical, and perceptual) on the perceived QoS. Fourthly, to develop a cognitive map that describes how pedestrians perceive their QoS considering the positive and negative effects over them when walking. Fifthly, to propose a model to forecast sidewalk QoS (SQoS) using objective (e.g., physical) and subjective (e.g., perceptions) attributes.

To fulfill the objectives of this research, 1056 pedestrian responses were gathered, considering their perceptions when walking, including their perception of the SQoS. In addition, data related to objective on-site attributes, was collected for 30 different sidewalks in the city of Bogotá. Then, to calculate the methodologies' performance in

Bogotá, the PPSI values were calculated using 28 different methodologies and compared with the pedestrian perception of the SQoS. Performance was evaluated through a match score calculation (the number of matches between the predicted value and the pedestrian perception of their QoS), by the difference between the predicted value and the pedestrian's QoS perception, and by a χ^2 test (which compares the forecasted value distribution and the SQoS data distribution). To analyze pure and joint effects of the different groups of predictors on the perceived QoS, 15 different models were developed that considered the groups individually, in pairs, and as groups of three and four. Then, for each of these models, the partial coefficient of determination (R^2) was used to identify the boundaries of the variance explanation for each group of attributes. Similarly, to quantify the proportion of the variance that is explained for each model adjusting for the number of explanatory terms and to test if all coefficients were significant, an adjusted R^2 and an F-test were used respectively. In addition, a SEM approach, using the data on pedestrian's perceptions, was used to propose a cognitive map that explains the way in which the QoS is perceived by pedestrians. Finally, in order to find the best model to forecast the SQoS, the dataset was divided into two parts: 70% to estimate the various forecasting models and 30% to validate them. The forecasting models were estimated using four different approaches: ordinary least squares (OLS), ordered probit, continuous multiple indicators and multiple causes (MIMIC), and ordered probit MIMIC. Then, the different models were validated and compared in terms of three measures mentioned above.

The methodologies that better represent Bogotá's local conditions in terms of match score were those based on expert judgment (mean = 32.78%). Of these methodologies, one proposed by Jaskiewicz (1999) was able to predict the SQoS of 15 out of 30 sidewalks in Bogotá. The second-most effective methodologies, based on match score, were those that use on-site objective attributes (mean = 22.14%). Of these, one proposed by Talavera-Garcia & Soria-Lara (2015) was able to predict the SQoS of 14 out of 30 sidewalks. Finally, the methodologies based on the flow-capacity relationship, had the lowest capability to evaluate Bogotá's local conditions (mean = 8.75%). Of these methodologies, one proposed by the Alcaldia Mayor de Bogota D.C. (2005) was able to predict the SQoS of eight out of 30 of the city's sidewalks. This is a version of the method proposed by the Transportation Research Board (2000) calibrated for the city of Bogotá; interestingly, when directly applied to Bogotá, it was able to predict only one out of 30 sidewalks (implying an increase of 23.33 percentual points when the methodology is calibrated to the city).

When the individual and joint effects of the different groups of predictors were considered, it was found that the perception attributes explained the majority of the total variance of the perceived QoS (between 0.372 and 0.579). The physical attributes explained between 0.021 and 0.225 of the total variance of the perceived QoS, the sociodemographic attributes explained only between 0.007 and 0.024, and the environmental attributes even less (between 0.003 and 0.010). Using the cognitive map to understand how pedestrians perceived the QoS, four latent variables were found that positively influenced pedestrians' perceptions (*sidewalk characteristics*, *surroundings*, *protection*, and *amenities*). On the other hand, three latent variables were found that negatively influenced the QoS perception by pedestrians (*externalities*, *discomfort*, and *bike hassles*). Finding these latent variables shows how cognitive maps can be used to understand how pedestrians perceived the QoS.

An analysis of the forecasting models revealed that the best performance indicators were obtained when using an ordered probit model to forecast the SQoS (match score = 96.67%, IQR = 0.705, χ^2 = 1.167). The OLS model received the second-best performance indicators (match score = 96.67%, IQR = 0.740, χ^2 = 1.543). However, to apply these models we require both objective (sidewalk and user attributes) and subjective (pedestrian perceptions) information. Of the models that only need user and sidewalk objective attributes to both explain the subjective attributes and forecast the SQoS, the ordered probit MIMIC was the best option (match score = 86.67%, IQR = 0.990, χ^2 = 1.281) and the continuous MIMIC received the worst results (match score = 83.33%, IQR = 1.343, χ^2 = 3.848).

We found that a direct application of methodologies to calculate the PPSI proposed in the literature would not provide a good representation of Bogotá's local context. Notwithstanding, we found that those based on expert judgment (subjective attributes) provided the better results (for calculating the PPSI) when they were directly applied in the city. In addition, we also found that calibrating the methodologies for the local context improves their performance. For this reason, to improve the performance of the forecasting of pedestrian perceived QoS, it is essential to understand the role and impact of subjective attributes on the perceived QoS and to create methodologies that consider the local context. Furthermore, the explanatory power of different groups of predictors were quantified and it was found that perceptual attributes have the highest boundaries of QoS proportion of the variance explained. However, to forecast the QoS or SQoS, it is recommended that all groups of attributes are used, considering that all contribute to the QoS variance explanation. Moreover, a cognitive map is presented that can potentially be used to describe the effects of the perception of on-site objective attributes on the latent variables found here, and in the pedestrian perception of the QoS. Finally, using the ordered probit MIMIC to forecast the SQoS with both objective and subjective attributes, it is possible to design pedestrian infrastructure that improves the walking experience and counteracts the negative effects experienced by pedestrians when walking. Additionally, this model can be used for practitioners, who can apply it to forecast the SQoS using only objective attributes from the users and the sidewalk.

On this study there are presented many evidences about the role of perceptions to explain or forecast the pedestrian QoS when walking. Using these evidences, it is possible to going deeper to continue with the expansion of knowledge in this area. First, it is recommended to explore other terms referring to the service that an infrastructure is rendering to its users like comfort, pleasure, stress, experience, or satisfaction. Second, the use of an ordered probit MIMIC approach to forecast the perceived QoS for urban sidewalks can be used as a base to propose other forecasting models considering the perceptual differences between the people of different cities. In addition, the MIMIC approach can be also proposed to develop a model to forecast the pedestrian perception of their QoS rather than the complete urban SQoS. Finally, this study can be used also a base to understand how different is perceived the SQoS considering the differences between pedestrians (e.g., sex, marital status, etc.).

Resumen ejecutivo

A nivel mundial se han desarrollado diversos indicadores para evaluar el desempeño o servicio de infraestructura peatonal (PPSI) en aceras urbanas, tales como el nivel de servicio peatonal (PLOS) o la calidad de servicio (QoS). Para el desarrollo de estas metodologías se han utilizado diferentes aproximaciones donde se consideran principalmente tres tipos de atributos para explicar los PPSI (relación flujo-capacidad, atributos objetivos y juicio de expertos). De estos grupos se han identificado una variedad de predictores (ambientales, sociodemográficos, físicos y de percepción) que tienen potencial de ser utilizados para explicar la percepción de QoS.

Sin embargo, a partir de la literatura se puede sugerir que el desempeño de las diversas metodologías dependen del sitio en el cual son aplicadas (Hasan et al., 2015). Adicionalmente, no existen muchos estudios que comparen los resultados de las predicciones de las metodologías considerando la aproximación de cada una de ellas. Cuando se consideran los predictores tampoco hay muchos estudios que cuantifiquen el efecto individual y en conjunto de los diferentes grupos de predictores en términos de la explicación de la varianza de la QoS percibida. Adicionalmente, cuando se busca explicar la manera en la cual los peatones perciben los PPSI considerando sus interacciones al caminar, Geetha Rajendran Bivina & Parida (2019) desarrollaron un modelo de ecuaciones estructurales (SEM) donde de explican únicamente los efectos positivos sobre el PLOS generados por las percepciones de los peatones al caminar.

Por esta razón, esta investigación tiene como propósitos primero probar el desempeño de las diferentes metodologías para calcular los PPSI considerando las diferentes aproximaciones de estas. A partir de este desempeño también se busca analizar la aplicación de estas metodologías en la ciudad de Bogotá. De igual manera, se busca analizar el efecto individual y en conjunto de los diferentes grupos de predictores (ambientales, sociodemográficos, físicos y de percepción) sobre la QoS percibida. Posteriormente, se busca desarrollar un mapa cognitivo que describa la forma en la cual los peatones perciben su QoS a partir de los efectos positivos y negativos resultantes de las interacciones de los peatones al caminar. Finalmente, se busca proponer un modelo para pronosticar la QoS de las aceras utilizando atributos objetivos y subjetivos.

Para cumplir los objetivos de esta investigación inicialmente se recolectaron 1056 respuestas de peatones referentes a sus percepciones al caminar incluyendo su percepción sobre la QoS de la acera al igual que datos objetivos en el sitio en 30 aceras diferentes de la ciudad de Bogotá. Para calcular el desempeño de las diferentes metodologías en la ciudad de Bogotá se compararon los valores de PPSI resultantes de la aplicación de cada metodología con las percepciones peatonales sobre su QoS. Posteriormente, el desempeño se evaluó a partir a partir del cálculo del puntaje de emparejamiento (número de veces en la cual el valor de la metodología coincide con la percepción peatonal sobre su QoS) y la variabilidad del error (diferencia entre el valor de la metodología y la percepción peatonal sobre su QoS).

Para analizar el efecto individual y en conjunto de los diferentes grupos de predictores sobre la QoS percibida se desarrollaron quince modelos diferentes considerando los grupos de manera individual, en parejas, tríos y cuartetos. Posteriormente, se calculó el coeficiente de determinación (r-cuadrado) parcial de cada uno de los modelos mencionados anteriormente para encontrar los limites superior e inferior de la varianza explicada por cada uno de los grupos. De forma similar, se utilizó el r-cuadrado ajustado y la prueba F para cuantificar la explicación de la varianza de cada modelo ajustando por el número de variables independientes y para conocer la significancia de los coeficientes de los modelos respectivamente. A continuación, con el fin de proponer un mapa cognitivo que pudiera explicar la forma en la cual la QoS es percibida por los peatones se utilizó un SEM a partir de las percepciones peatonales.

Finalmente, para proponer un modelo que permita pronosticar la QoS en aceras inicialmente se dividió el conjunto de datos en dos: 70% para desarrollar los modelos de pronóstico y 30% para validarlos. Los modelos de pronóstico se desarrollaron a partir de cuatro aproximaciones diferentes: mínimos cuadrados ordinarios (MCO), probit ordenados, múltiples indicadores y múltiples causas (MIMIC) continuo y MIMIC probit ordenados. Posteriormente, los diferentes modelos fueron validados y comparados utilizando el puntaje de emparejamiento, la variabilidad del error y la prueba de χ^2 (comparación entre la distribución de los valores pronosticados de la QoS y la distribución de los datos observados de QoS).

Las metodologías que mejor representan las condiciones de Bogotá considerando el puntaje de emparejamiento son aquellas basadas en juicio de expertos (media = 32.78%).

De estas metodologías se encontró que la propuesta por Jaskiewicz (1999) puede pronosticar la QoS percibida en 15 de cada 30 aceras en Bogotá. En segunda posición considerando el puntaje de emparejamiento se encuentran las metodologías basadas en atributos objetivos (media = 22.14%). De estas metodologías se encontró que la propuesta por Talavera-Garcia & Soria-Lara (2015) puedes pronosticar la QoS percibida en 14 de cada 30 aceras en Bogotá. Finalmente, las metodologías basadas en la relación flujo-capacidad son las que tienen menor capacidad de evaluar las condiciones locales de Bogotá en términos de pronóstico de QoS (media = 8.75%). De estas metodologías se encontró que la propuesta por la Alcaldia Mayor de Bogota D.C. (2005) puede pronosticar la QoS percibida en 8 de cada 30 aceras en Bogotá. La metodología propuesta por la Alcaldia Mayor de Bogota D.C. (2005) es una versión calibrada para la ciudad de Bogotá de la metodología propuesta por el Transportation Research Board (2000) la cual al ser aplicada directamente puede pronosticar 1 de cada 30 aceras en Bogotá. Esto quiere decir que la calibración desarrollada permitió un incremento de 23.33 puntos porcentuales probando los beneficios sobre la capacidad de las metodologías que se pueden generar a partir de calibraciones considerando el contexto local.

Cuando se consideran los efectos individuales y en conjunto de los diferentes grupos de predictores, se encontró que los atributos de percepción son los que mayor variabilidad explican de la QoS percibida (entre 0.372 y 0.579). En segundo lugar, los atributos físicos son los que siguen en cantidad de explicación de la variabilidad total de la QoS percibida (entre 0.021 y 0.225). Posteriormente, los atributos sociodemográficos son unos de los que menos explican la variabilidad total de la QoS percibida (entre 0.007 y 0.024). Finalmente, los atributos ambientales son los que menos explican la variabilidad total de la QoS percibida (entre 0.003 y 0.010). Considerando el desarrollo del mapa cognitivo para entender como los peatones perciben su QoS se encontraron cuatro variables latentes que influencian positivamente la QoS que perciben los peatones (características de la acera, alrededores, protección y servicios e instalaciones). Por otro lado, se encontraron tres variables latentes que influencian negativamente la QoS percibida por los peatones (externalidades, incomodidad y molestias con bicicletas). A partir de las variables latentes descubiertas se propone el mapa cognitivo que se puede utilizar para entender como los peatones perciben su QoS.

Considerando los modelos de pronóstico, cuando se busca pronosticar la QoS de la acera a partir del modelo probit ordenado se obtienen los mejores indicadores de desempeño al ser validado (puntaje de emparejamiento = 96.67%, RQ = 0.705, χ^2=1.167). En términos de indicadores de desempeño, el modelo MCO se localiza en segunda posición (puntaje de emparejamiento = 96.67%, RQ = 0.740, χ^2=1.543). Sin embargo, para aplicar estos modelos se necesita obtener información tanto objetiva como subjetiva. Al considerar modelos que solo necesiten como variables de entrada datos objetivos de los usuarios y las aceras para pronosticar la QoS, el modelo MIMIC probit ordenado se localiza en primera posición (puntaje de emparejamiento = 86.67%, RQ = 0.990, χ^2=1.281). Finalmente, el modelo MIMIC continuo se localiza en última posición (puntaje de emparejamiento = 83.33%, RQ = 1.343, χ^2=3.848).

A partir de esta investigación se encontró que al aplicar en Bogotá directamente las diversas metodologías propuestas en la literatura para calcular los PPSI no se obtiene una buena representación del contexto local de la ciudad. Sin embargo, se encontró que de las metodologías existentes aquellas que se basan en juicio de expertos (atributos subjetivos) son las que proveen mejores resultados al calcular el PPSI directamente en Bogotá. Adicionalmente, se encontró que el calibrar las metodologías al contexto local mejora el desempeño de las metodologías. Por estas razones, se encontró que el entender el rol e impacto de los atributos subjetivos sobre la calidad de servicio percibida y generar metodologías considerando el contexto local mejorará el desempeño del cálculo de la QoS percibida por los peatones. Adicionalmente, se cuantificó el poder explicativo de diferentes grupos de predictores donde los atributos de percepción son aquellos que tienen los limites inferiores y superiores de mayor magnitud al explicar la variabilidad de la QoS percibida. A pesar de esto, para pronosticar la QoS percibida en las aceras se recomienda la utilización de todos los grupos de atributos debido a que todos ellos aportan a la explicación de la variabilidad de la QoS percibida. Adicionalmente, se presenta un mapa cognitivo con potencial de ser utilizado para describir los efectos de las percepciones peatonales sobre atributos objetivos y la QoS a partir de las variables latentes encontradas. Finalmente, es posible desarrollar infraestructura peatonal que mejore la experiencia de caminata de los peatones y que mitigue los efectos negativos que se pueden generar sobre los peatones al caminar, a partir del modelo propuesto para pronosticar la QoS en aceras. Adicionalmente, se propone un modelo para la utilización por parte de profesionales que puede ser aplicado para predecir la QoS de las aceras a partir de variables objetivas de los usuarios y aceras donde ya se han involucrado las percepciones de los peatones (MIMIC probit ordenado).

En este estudio se presentan evidencias sobre el rol que tienen las percepciones para explicar y pronosticar la QoS de los peatones al caminar. Por medio de estas evidencias, es posible profundizar en la investigación para continuar con la expansión del conocimiento en esta área. Primero, se recomienda explorar otros términos que se refieren al servicio que una infraestructura peatonal le provee a sus usuarios como lo son el confort, placer, estrés, experiencia o satisfacción. Segundo, el uso de un modelo MIMIC probit ordenado para pronosticar como los peatones perciben la QoS de una acera urbana se puede utilizar como base para proponer otros modelos de pronóstico considerando las diferencias de percepción existentes entre las personas de diferentes ciudades. Adicionalmente, los modelos MIMIC también pueden ser utilizados como base para proponer modelos de pronóstico enfocados en el individuo mas que en la acera completa. Finalmente, este estudio puede ser utilizado como base para entender las diferencias que pueden existir sobre la percepción de la QoS de la acera basados en las diferencias que se pueden presentar entre los peatones (e.g., sexo, estado civil, etc.).

Publications

Through the development of this doctoral research we prepared publications for journals and conferences. There are nine journal publications proposed of which five are under review and four are papers in process to be submitted. We also attended five conferences already and there is one other conference in process to be attended.

Journal papers

- **Vallejo-Borda, J.A.**, Rosas-Satizabal, D. & Rodriguez-Valencia, A. (2019). Do attitudes and perceptions help to explain bicycle infrastructure quality of service? *Transportation Research Part D: Transport and Environment* (under review)

- **Vallejo-Borda, J. A.**, Ortiz-Ramirez, H.A., Rodriguez-Valencia, A., Hurtubia, R. & Ortúzar, J. de D. (2019). Forecasting the quality of service of Bogota's sidewalks: an ordered probit MIMIC approach. *Transportation Research Record* (in-Press)

- Rodriguez-Valencia, A., Barrero, G.A., Ortiz-Ramirez, H.A. & **Vallejo-Borda, J.A.** (2019). The power of users' perceptions in pedestrian quality of service. *Transportation Research Record* (under review).

- **Vallejo-Borda, J.A.**, Cantillo, V. & Rodriguez-Valencia, A. (2019). A perception based cognitive map of the pedestrian perceived quality of service on urban sidewalks. *Transportation Research Part F: Traffic Psychology and Behaviour* (under review).

- **Vallejo-Borda, J.A.**, Ortiz-Ramirez, H.A., Rodriguez-Valencia, A., Cantillo, V. & Ortuzar, J. de D. (2019). Perception based methodological approaches to forecast the pedestrian quality of service on urban sidewalks. *Transportation Research Part B: Methodological* (working paper).

- Ortiz-Ramirez, H.A., **Vallejo-Borda, J.A.** & Rodriguez-Valencia, A. (2019). Testing the Mehrabian-Russell model in pedestrian approach-avoidance behavior when walking on urban sidewalks. *Journal of Environmental Psychology* (working paper).

- Rodriguez-Valencia, A., Barrero, G.A., Ortiz-Ramirez, H.A. & **Vallejo-Borda, J.A.** (2019). The power of users' perceptions: pedestrian and bicycle level of service and quality of service revisited. *International Journal of Sustainable Transportation* (working paper).

- **Vallejo-Borda, J.A.**, Cantillo, V., Rodriguez-Valencia, A., Eboli, L., Forciniti, C. & Mazzulla, G. (2019). Effects of perceptions in pedestrian quality of service: a literature review. *Transport Reviews* (working paper).

Conferences

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Contents

Abbreviations

A: Average pedestrian age

BP: Bicyclist presence

BW: Buffer width

DP: Driveway length

HGV: Heavy goods vehicles

HP: Potholes presence

LOS: Level of service

MAUT: Multi-Attribute Utility Theory

MIMIC: Multiple Indicators and Multiple Causes

MSP: Median street presence

OLS: Ordinary least squares

PLOS: Pedestrian level of service

PPSI: Pedestrian performance or service indicators

QoS: Quality of service

R^2: Coefficient of determination

SEM: Structural equation modelling

SQoS: Sidewalk quality of service

SW: Sidewalk width

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1. **Introduction**

In recent years, there has been progress toward the better measurement or evaluation of the service, quality or performance of pedestrian infrastructure. Several pedestrian performance or service indicators (PPSI) have been developed, such as the pedestrian level of service (PLOS), which in transportation planning is the most traditional PPSI that seeks to explain how pedestrians are served by the infrastructure. This PPSI is based on the traditional level of service (LOS) which is a qualitative stratification of performance measures that represents the quality of a transport infrastructure. This methodology allows researchers to determine the quality that an infrastructure renders over a certain time on a six-point ordinal scale (Roess & Prassas, 2014; Transportation Research Board, 2000, 2010, 2016). LOS is frequently used for motorized traffic on highways, urban roads, intersections, roundabouts, etc. The main principle behind LOS for motorized vehicles is the demand-capacity relationship (i.e., the level of congestion). Therefore, traffic flow variables like speed, density, and flow are frequently used to calculate the LOS.

The first methodologies for the calculation of PLOS only considered the flow-capacity relationship (Fruin, 1971). In the 2000s, research on PLOS found other factors beyond the demand-capacity analysis that explain pedestrian satisfaction from a walker's experience of a certain place. The Transportation Research Board (2010) defines eight quantitative criteria that may affect PLOS based on capacity. However, pedestrians usually interact with other transportation modes, sharing more than capacity criteria with the other modes, affecting the perception of PLOS. These interactions are evident in research that identifies the different criteria affecting PLOS. For example, B. Landis, Vattikuti, Ottenberg, McLeod, & Guttenplan, (2001) use vehicle flow variables (flow and speed) and lateral separation to calculate PLOS. Additionally, Pikora, Giles-Corti, Bull, Jamrozik, & Donovan (2003) use criteria like signaling, tree planting, and rest furniture to measure PLOS. Similarly, Jaskiewicz (1999) uses pedestrian interaction with facades and architecture to measure PLOS. Additionally, other authors have shown that criteria like traffic pollution, road safety, and personal security are perceived as variables that affect PLOS (Rodriguez-Valencia, Paris, & Vallejo-Borda, 2017).

Most methods used to calculate the PPSI are usually based on measurable physical features. Furthermore, even the more sophisticated PPSI methods available might still be site-dependent. Hasan, Siddique, Hadiuzzaman, & Musabbir (2015) found that methodologies to calculate PPSI developed in a different place from where they were applied represented at most 72% of the new local conditions; they also found that most of the US-based methodologies represented less than 50% of the local conditions in Dhaka City. However, there are not many studies that identify how current state-of-the-practice methods to evaluate PPSI are able to represent the local conditions of cities in Colombia or other Latin-American countries. Also, it is not possible to be confident in the results of the PPSI methods applied in Bogotá, because these methods do not represent the city's context and characteristics (Á. Rodríguez & Unda, 2015).

In addition, walking implies a sensorial experience within the surrounding environment that affects the perceived quality of service (QoS), but it is not clear how much of the pedestrian perception of the QoS is explained by their perceptions of the interactions they have when walking. Similarly, it is not clear how pedestrians interact with the sidewalk to later evaluate the QoS from their perceptions.

Pedestrian perceptions are not considered much in the literature for the evaluation of the QoS perceived by pedestrians. However, QoS is not what is offered, but what the user receives (Drucker, 2006). Additionally, it can be hypothesized that the perceived QoS is affected by more than objective attributes, and the sensorial experience of pedestrians when walking must be considered. Fernández-Heredia, Jara-Díaz, & Monzón (2016) mentioned that including perceptions in choice models enhanced the model's goodness of fit and its performance. In addition, an improvement in the understanding of pedestrian perceptions when considering subjective attributes to explain the perceived QoS can create an opportunity for the benefit of pedestrians.

The main objective of this study is to evince the role and effect of pedestrian perceptions on their QoS and on the QoS forecasting on urban sidewalks. For this reason, on this study initially it is going to be tested if PPSI methodologies are in fact site-dependent, by forecasting the PPSI in Bogotá using 28 methodologies proposed worldwide, and comparing them with the pedestrian perceptions of QoS when walking. Then, to explore the power of perceptions that explain the QoS as perceived by pedestrians, different models to explain perceived QoS will be developed by combining different attributes as independent variables in groups (environmental, sociodemographic, physical and perceptual), and calculating goodness-of-fit (i.e. partial R^2, adjusted R^2, and F statistics). Then, to find out if there are latent variables behind the perceived QoS and the relationships between them, a pedestrian cognitive map will be proposed, explaining the perceived QoS by means of structural equation models (SEM) and using the perceptions recorded. Finally, to develop a sidewalk QoS (SQoS) forecasting model that considers both objective and subjective attributes, four different approaches will be used: OLS (Fruin, 1971; S. Kim, Choi, & Kim, 2013; S. S. Kim, Choi, Kim, & Tay, 2014; Mōri & Tsukaguchi, 1987; Muraleetharan, Adachi, Hagiwara, & Kagaya, 2005; Polus, Schofer, & Ushpiz, 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985, 2000), ordered probit (Choi, Kim, Min, Lee, & Kim, 2016; Jensen, 2007; Kang & Fricker, 2016; Kang, Xiong, & Mannering, 2013; Muraleetharan & Hagiwara, 2007), and continuous and ordered probit multiple indicator multiple causes (MIMIC) (Geetha Rajendran Bivina & Parida, 2019).

This research also aims to explore the role of users' perceptions as input variables in the explanation of the quality of service of a sidewalk. The study comprises the following questions: How have users and their perceptions been considered as predictors for service or performance in the past? To what extent can pedestrian perceptions explain the sidewalk QoS? And finally, how can perceptions be applied and what methods are better to forecast QoS? To achieve the main research objective and to answer the questions, the following specific objectives have been established:

- To analyze the role of perceptions and physical attributes in the PPSI calculation.
- To analyze the evolution of the main PPSI methodologies and to evaluate their applicability for Bogotá's local context.
- To quantify the contribution of perception attributes in the explanation of QoS.
- To propose a perceived QoS cognitive map from pedestrian perceptions.
- To forecast the QoS and SQoS for pedestrians in the city of Bogotá.

This document includes a complete literature review that describes the evolution of PPSI and the interaction between perception and the PPSI. Then, the methodology section explains how the doctoral project was developed. After, the performance results for the 28 PPSI methodologies applied in Bogotá are presented. Subsequently, the contribution of perceptions to the explanation of QoS are quantified and a cognitive map to understand how pedestrians perceive the QoS is proposed. Then, two forecasting models for the SQoS that can be applied on the different sidewalks of Bogotá and one forecasting model to predict the users' QoS are proposed. Next, the different results of the previous steps are discussed and analyzed. Finally, the conclusions of the study are presented with reference to the research question, the main objective, the specific objectives, the results, and the discussion and analysis sections.

2. Literature review

Many PPSI have been proposed over the years to evaluate pedestrian performance or service indicators. PLOS was initially proposed in the 1970s by Fruin (1971) and was based on the level of service (LOS) methodology developed for motor vehicles by the Bureau of Public Roads (1950). Then, in the 1980s, PPSI options were expanded by the addition of quality of service (QoS) as a definition for LOS (Transportation Research Board, 1985) and pedestrian comfort (Mōri & Tsukaguchi, 1987). In the 1990s, the PPSI spectrum increased again through the addition of other terms such as stress (Mozer, 1994) and experience (Jaskiewicz, 1999). Finally, in the twenty-first century, the PPSI spectrum was completed with the addition of the term satisfaction (Jensen, 2007). These PPSI are usually measured by asking users for their perspective on the overall PPSI provided by the infrastructure. In addition, the PPSI terms are usually used interchangeably in the literature to refer to the same output (service) related to pedestrians (see Table 2.1).

Table 2.1. The history of PPSI proposals

PLOS	(G. R. Bivina, Parida, Advani, & Parida, 2018; Carter et al., 2013; Christopoulou & Pitsiava-Latinopoulou, 2012; Dandan, Wei, Jian, & Yang, 2007; Fruin, 1971; Gallin, 2001; Jaskiewicz, 1999; Jensen, 2007; Kang et al., 2013; S. Kim et al., 2013; S. S. Kim et al., 2014; T. Kim, Park, Lim, & Joo, 2011; Landis et al., 2001; Marisamynathan & Lakshmi, 2016; Mōri & Tsukaguchi, 1987; Mozer, 1994; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Petritsch et al., 2006; Polus et al., 1983; Sahani, Ojha, & Bhuyan, 2017; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015; Tanaboriboon & Guyano, 1989; Tiznado-Aitken, Muñoz, & Hurtubia, 2018; Transportation Research Board, 1985, 2000, 2010, 2016)
QoS	(G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Dandan et al., 2007; T. Kim et al., 2011; Lee, Lee, Son, & Joo, 2013; Macdonald, Szibbo, Eisenstein, & Mozingo, 2018; Sahani et al., 2017; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2000, 2010, 2016, 1985)
Comfort	(Dandan et al., 2007; Kang et al., 2013; S. Kim et al., 2013; Landis et al., 2001; Marisamynathan & Lakshmi, 2016; Mōri & Tsukaguchi, 1987; Sarkar, 2003)
Stress	(Mozer, 1994)
Experience	(Jaskiewicz, 1999; Macdonald et al., 2018)
Satisfaction	(Choi et al., 2016; Jensen, 2007; S. Kim et al., 2013; T. Kim et al., 2011; Marisamynathan & Lakshmi, 2016; Sahani et al., 2017)

For the purpose of this chapter, and in the interests of the present doctoral research, this next section will document the attributes that have been considered at different points in time to understand the different PPSI on urban sidewalks and their evolution (Table 2.2 and Table 2.3).

Table 2.2. The evolution of PLOS attributes

Period	Main authors	Flow	Geometry	Surrounding	Environmental factors	Perception	Land uses	Population structure
1970 - 1979	(Fruin, 1971)	✓	✓					
1980 - 1989	(Polus, Schofer, & Ushpiz, 1983; HCM, 1985; Mori & Tsukaguchi, 1987; Tanaboriboon & Guyano, 1989)	✓	✓					
1990 - 1999	(Mozer, 1994; Jaskiewicz, 1999)	✓	✓	✓				
2000 - 2004	(HCM, 2000; Gallin, 2001; Landis et al, 2001; Pikora et al, 2003; Sarkar, 2003)	✓	✓	✓	✓	✓		
2005 - 2009	(Muraleetharan et al, 2005; Ewing et al, 2006; Petritsch et al, 2006; Jensen, 2007; Dandan et al, 2007; Muraleetharan & Hagiwara, 2007; FDOT, 2009)	✓	✓	✓	✓	✓	✓	
2010 - 2014	(HCM, 2010; Kim et al, 2011; Christopoulou & Pitsiava-Latinopoulou, 2012; Lee et al, 2013; Carter et al, 2013; Kim, Choi, & Kim, 2013; Kang, Xiong, & Mannering, 2013; Kim et al, 2014)	✓	✓	✓	✓	✓		✓
2015 - today	(Talavera-Garcia & Soria-Lara, 2015; HCM, 2016; Motamed & Bitaraf, 2016; Kang & Fricker, 2016; Choi et al, 2016; Marisamynathan & Lakshmi, 2016; Sahani, Ojha, & Bhuyan, 2017; Macdonald et al, 2018; Bivina et al, 2018)	✓	✓	✓	✓	✓	✓	✓

In the early 1970s, the LOS calculation methodology was taken as a guide to propose a PLOS calculation methodology that considered only flow and geometry attributes (Fruin, 1971). These attributes were the only ones considered to calculate PLOS until the end of the 1980s (Mōri & Tsukaguchi, 1987; Polus et al., 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985).

During the 1990s, the evolution of PLOS started with the consideration of new attributes that recognized pedestrian interactions while walking. Initially, the addition of attributes concerning the surroundings supported the PLOS calculation along with the flow and geometry attributes (Jaskiewicz, 1999; Mozer, 1994). Then, this evolution continued at the beginning of the twenty-first century with the addition of attributes relating to the environment (Pikora et al., 2003; Sarkar, 2003) and the perceptions of experts (Gallin, 2001; Pikora et al., 2003; Sarkar, 2003) to the PPSI calculation.

After the year 2000, the importance of land use and population structure also emerged in PPSI calculation methodologies. From 2005 to 2009, only land use was added to the above-mentioned attributes to improve PPSI calculation methodologies (Jensen, 2007). Then, from 2010 to 2014, population structure was considered as an attribute, but land use was omitted (Kang et al., 2013). However, in the literature from 2015 until today, all the above-mentioned attributes are considered in the cutting-edge PPSI calculation methodologies. There are methodologies that consider both expert judgement and on-site measurable attributes of the sidewalks (G. R. Bivina et al., 2018), land uses (Choi et al., 2016), population structure (Kang & Fricker, 2016), physical attributes of the right of way (Macdonald et al., 2018; Marisamynathan & Lakshmi, 2016; Sahani et al., 2017; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2016), and environmental attributes of the surrounding (Motamed & Bitaraf, 2016) to calculate the different PPSI.

Researchers worked on the evolution described above due to the need to improve pedestrian infrastructures and improve the pedestrians' QoS. However, to achieve this goal, it is necessary to consider how pedestrians are influenced by their surroundings when walking (G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999; Pikora et al., 2003; Sarkar, 2003). Nonetheless, it is not only necessary to consider these influences, but it is also important to revise how researchers introduced them into the different PPSI methodologies. For this reason, Table 2.3 chronicles the attributes that have been considered to determine the PPSI over time.

Table 2.3. Historical review of PPSI methodology attributes

(Author, year)	Method	Data	Country	Attributes considered
(Fruin, 1971)	Ordinary least squares regression	Video	United States	Pedestrian density, pedestrian flow; pedestrian space; sidewalk width
(Polus et al., 1983)	Ordinary least squares regression	Video	Israel	Pedestrian density; pedestrian flow; pedestrian space; sidewalk width
(Transportation Research Board, 1985)	Ordinary least squares regression	Video	United States	Pedestrian density; pedestrian flow; pedestrian space; sidewalk width
(Mōri & Tsukaguchi, 1987)	Ordinary least squares regression	Video and surveys	Japan	Pedestrian density; pedestrian flow; sidewalk width
(Tanaboriboon & Guyano, 1989)	Ordinary least squares regression	Video	Thailand	Pedestrian flow; pedestrian space
(Mozer, 1994)	Scoring system	Experts opinion	United States	Buffer width; driveways segment; heavy vehicles factor; number of driveways; number of lanes; pedestrian flow; sidewalk width; vehicular flow; vehicular speed
(Jaskiewicz, 1999)	Scoring system	Experts opinion	United States	Buffer; building articulation; complexity of spaces; connectivity; enclosure / definition; lighting; overhangs / awnings / varied roof lines; shade trees; sidewalk condition; transparency; vehicular speed
(Transportation Research Board, 2000)	Ordinary least squares regression	Video	United States	Pedestrian flow; pedestrian space; pedestrian speed; sidewalk width
(Gallin, 2001)	Scoring system	Experts opinion	Australia	Access; buffer width; connectivity; crossing opportunities; mix of path users; number of driveways; pedestrian flow; security; sidewalk condition; sidewalk width; support facilities
(Landis et al., 2001)	Stepwise regression analysis	Survey	United States	Bike lane width; buffer width; number of lanes; on street parking segment; outside lane width; shoulder width; sidewalk width; vehicular flow; vehicular speed
(Pikora et al., 2003)	Delphi study	Experts opinion	Australia	Amenities; bus stop presence; cleanliness; crossing opportunities; land uses; lighting; pollution; safety; sidewalk condition; vehicular speed
(Sarkar, 2003)	Scoring system	Experts opinion	United States	Access; buffer; noise; overhangs / awnings / varied roof lines; pedestrian speed; pollution; sidewalk condition; sidewalk furniture

(Muraleetharan et al., 2005)	Ordinary least squares regression	Survey and expert's opinion	Japan	Bike flow opposite direction; bike flow same direction; bike lane width; bike speed; buffer width; obstructions; on street parking segment; pedestrian flow; pedestrian speed; shoulder width; sidewalk width
(Ewing, Handy, Brownson, Clemente, & Winston, 2006)	Multivariate statistics	Video and surveys	United States	Comfort; connectivity; enclosure / definition; pedestrian flow; safety; sidewalk width; street width; transparency; vehicular flow; weather
(Petritsch et al., 2006)	Stepwise regression analysis	Survey	United States	Driveways segment; vehicular flow
(Jensen, 2007)	Cumulative logit regression	Video and surveys	Denmark	Bike flow; buffer width; landscape; land uses; lanes width; median street presence; number of lanes; on street parking segment; pedestrian flow; sidewalk width; trees presence; vehicular flow; vehicular speed
(Dandan et al., 2007)	Stepwise regression analysis	Survey	China	Bike flow; buffer width; driveway segment; pedestrian flow; vehicular flow
(Muraleetharan & Hagiwara, 2007)	Multinomial logit model	Survey	Japan	Bike flow opposite direction; bike flow same direction; bike speed; buffer width; crossing opportunities; obstructions; on street parking segment; pedestrian flow; pedestrian speed; shoulder width; sidewalk width
(State of Florida Department of Transportation, 2009)	Stepwise regression analysis	Survey	United States	Bike lane width; buffer width; number of lanes; on street parking segment; outside lane width; shoulder width; sidewalk width; vehicular flow; vehicular speed
(Transportation Research Board, 2010)	Stepwise regression analysis	Survey	United States	Bike lane width; buffer; buffer width; number of lanes; on street parking segment; outside lane width; pedestrian space; shoulder width; sidewalk width; vehicular flow; vehicular speed
(T. Kim et al., 2011)	Multi criteria decision analysis	Video and surveys	South Korea	Landscape; pedestrian flow; sidewalk condition; support facilities
(Christopoulou & Pitsiava-Latinopoulou, 2012)	Scoring system	Survey	Greek	Access; buffer; buffer width; bus stop presence; driveways segment; maneuver freedom; noise; obstructions; pedestrian flow; ramps; safety; sidewalk condition; sidewalk furniture sidewalk width; trees presence; vehicular flow; vehicular speed
(Lee et al., 2013)	Multi criteria decision analysis	Survey	South Korea	Amenities; connectivity; pedestrian space; pedestrian speed
(Carter et al., 2013)	Scoring system	Survey	United States	Buffer; buffer width; lanes width; number of lanes; on street parking segment; sidewalk length; sidewalk width; vehicular flow; vehicular speed limit

(S. Kim et al., 2013)	Ordinary least squares regression	Survey	South Korea	Buffer width; lanes width; sidewalk width; vehicular flow; vehicular speed
(Kang et al., 2013)	Ordered probability model	Survey	China	Age; amenities; bike flow; bike flow opposite direction; bike flow same direction; bike speed; buffer; lighting; on street parking segment; pedestrian flow; sidewalk width; weather
(S. S. Kim et al., 2014)	Ordinary least squares regression	Video and surveys	South Korea	Pedestrian density; pedestrian flow; pedestrian space; pedestrian speed; sidewalk width
(Talavera-Garcia & Soria-Lara, 2015)	Scoring system	Survey	Spain	Amenities; connectivity; sidewalk width; trees presence; vehicular speed
(Transportation Research Board, 2016)	Stepwise regression analysis	Survey	United States	Bike lane width; buffer; buffer width; number of lanes; on street parking segment; outside lane width; pedestrian space shoulder width; sidewalk width; vehicular flow; vehicular speed
(Motamed & Bitaraf, 2016)	Scoring system	Experts opinion	Iran	Access; amenities; buffer; building articulation; cleanliness; complexity of spaces; crossing opportunities; driveway segment; land uses; landscape; lighting; noise; number of lanes; on street parking segment; pollution; public toilet presence; security; sidewalk condition; sidewalk furniture; sidewalk width; trees presence; vehicular flow; vehicular speed
(Kang & Fricker, 2016)	Ordered probability model	Video and surveys	China	Age; bike flow; bike speed; buffer; genre; household size; marital status; number of lanes; pedestrian flow; pedestrian speed; sidewalk width; trees presence; weather
(Choi et al., 2016)	Ordered probability model	Survey	South Korea	Bike lane presence; bus stop presence; crossing opportunities; driveways segment; land uses; median street presence; number of lanes; pedestrian flow; sidewalk width; trees presence
(Marisamynathan & Lakshmi, 2016)	Stepwise regression analysis	Video and surveys	India	Buffer; sidewalk condition; sidewalk width; vehicular flow
(Sahani et al., 2017)	Stepwise regression analysis	Survey	India	Bike flow; bike lane width; buffer width; obstructions; on street parking segment; peddlers' segment; sidewalk width; vehicular flow; vehicular speed
(Macdonald et al., 2018)	Scoring system	Experts opinion	United States	Access; buffer; building articulation; crossing opportunities; enclosure; number of lanes; shade trees; sidewalk width; transparency
(G. R. Bivina et al., 2018)	Scoring system	Survey	India	Access; buffer; cleanliness; comfort; crossing opportunities; obstructions; security; sidewalk condition; sidewalk width
(Geetha Rajendran Bivina & Parida, 2019)	Structural Equation Modelling	Survey	India	Access, amenities, bus stop presence cleanliness, lighting, obstructions, pedestrian flow, security, sidewalk condition, sidewalk continuity, sidewalk width, vehicular flow, vehicular speed

The attributes considered for the first attempt at PLOS calculation were pedestrian density and space, these being very similar to the attributes considered to calculate motor vehicles' LOS. The idea behind the use of these attributes considered that there would be a positive correlation between the pedestrian's space and the PLOS. This means that if there were more space for a pedestrian to use, the PLOS of that sidewalk also improved. Similarly, the correlation between the PLOS and pedestrian density was considered negative. This is because with high densities, the crowd that formed would impact the PLOS in a negative way (Fruin, 1971; Mōri & Tsukaguchi, 1987; Polus et al., 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985).

Over the following years, some researchers started to include other attributes to calculate the PPSI besides those already considered. For example, the inclusion of pedestrian speed was considered as an important attribute for PPSI calculation because of the idea of these times about the pedestrians' need to complete their trips quickly (Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Transportation Research Board, 2000). Similarly, attributes that consider the interaction with other modes that might affect the pedestrians' trips like the buffer width, vehicular flow, vehicular speed, number of vehicular lanes, driveways, and the heavy goods vehicle (HGV) factor were also considered (Mozer, 1994).

However, during the same period, a theory also emerged that considered pedestrian interaction with the surroundings when walking in three different aspects: architectural, amenities, and road safety. The architectural aspect considered the provision of good spaces for pedestrians on the sidewalk in terms of space definition, connectivity, and friendly facades (non-continuous) to generate a positive PPSI. Similarly, for the amenities aspects, the literature considered that providing shade from trees, facades with transparent areas, and good sidewalk conditions were important to provide a good PPSI. Finally, this theory also considered road safety in the generation of a good PPSI with the inclusion of the buffer and vehicular speed attributes (Jaskiewicz, 1999).

The advancing methodologies included new attributes that allowed for an understanding of pedestrian needs and feelings with more accuracy using environmental attributes and expert judgement. In general, the attributes did not change, instead, the way of understanding these attributes was modified by the consideration of pedestrians and expert perceptions of each of them (Gallin, 2001; Landis et al., 2001; Pikora et al., 2003). Nonetheless, with the consideration of environmental attributes, new attributes that might influence the PPSI like pollution, noise, and lighting were considered (Pikora et al., 2003; Sarkar, 2003). However, these attributes stopped being considered in the literature related with pedestrian service indicators for around ten years until they were reintroduced in the 2010s (Christopoulou & Pitsiava-Latinopoulou, 2012; Kang et al., 2013; Motamed & Bitaraf, 2016).

Some studies started to consider pedestrian interaction with other transport modes where authors focused on the interaction that pedestrians may have with bicycles on the sidewalk and how these interactions may negatively impact the PPSI (Dandan et al., 2007; Jensen, 2007; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; State of Florida Department of Transportation, 2009). In addition, the interaction between pedestrians and other transportation modes using the adjacent transportation infrastructure was also considered to negatively impact walking activity (D. A. Rodríguez, Aytur, Forsyth, Oakes, &

Clifton, 2008) and the PPSI (Dandan et al., 2007; Ewing et al., 2006; Jensen, 2007; Muraleetharan & Hagiwara, 2007; Petritsch et al., 2006; State of Florida Department of Transportation, 2009). However, one of the most relevant aspects in understanding the PPSI was the inclusion of the term "comfort" to the attributes mentioned above (Ewing et al., 2006; Landis et al., 2001; Mōri & Tsukaguchi, 1987).

In the vanguard literature there are few changes to PPSI calculation methodologies. Chiefly, the main attributes considered over time are also considered in the most recent period (G. R. Bivina et al., 2018; Carter et al., 2013; Choi et al., 2016; S. Kim et al., 2013; S. S. Kim et al., 2014; T. Kim et al., 2011; Lee et al., 2013; Macdonald et al., 2018; Marisamynathan & Lakshmi, 2016; Sahani et al., 2017; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2010, 2016). Additionally, nowadays, the use of the term "comfort" is also considered (G. R. Bivina et al., 2018; Dandan et al., 2007; Kang et al., 2013; Marisamynathan & Lakshmi, 2016). One of the most notable inclusions was the use of population structure data (i.e., age, sex, marital status, and household size) to characterize pedestrians and the way that these pedestrian groups perceive the PPSI (Kang & Fricker, 2016; Kang et al., 2013). In other studies, a new line of research was also developed where an understanding of how the design of walkable areas contributes to the perception of QoS using stated preferences from image-based experiments (Adkins, Dill, Luhr, & Neal, 2012; Borst, Miedema, de Vries, Graham, & van Dongen, 2008; Ewing & Handy, 2009; Hurtubia, Guevara, & Donoso, 2015).

Up to this point in the chapter, the literature has been presented from the researcher's perspective, concentrating on the evolution of the PPSI. This due to the fact that there is not much information about how pedestrians perceive and understand the PPSI. Geetha Rajendran Bivina & Parida (2019) proposed a structural equation modelling (SEM) approach to explain the influence that the built environment has on the perceived PLOS in India. This approach was based on pedestrian perceptions and found four latent variables (safety, security, mobility, and infrastructure, and comfort and convenience) that positively impacted the perceived PLOS (Geetha Rajendran Bivina & Parida, 2019). However, there are not many studies that consider pedestrian perception of the QoS and the negative impacts that can be generated on this QoS from subjective attributes (e.g., perceptions). For this reason, it is necessary to expand on the knowledge of this topic by considering the sidewalk users' point of view. This consideration has been taken into account in other transportation areas, where the inclusion of users' perceptions improves the models' performance (Fernández-Heredia et al., 2016). For this reason, based on the literature and the satisfaction theories contained within, a structure of how pedestrians perceive and understand the PPSI will be hypothesized.

It has been established in the literature on satisfaction theories that there are direct and positive effects generated on the user's satisfaction from their perceived QoS. In addition, it has also been proven that users' perceptions of the different elements with which they interact positively or negatively impacts their walking activity (Schwartz, Aytur, Evenson, & Rodríguez, 2009) and their perception of the QoS (Aliman, Hashim, Wahid, & Harudin, 2016; Badara et al., 2013; Nilplub, Khang, & Krairit, 2016; Subramanian, Gunasekaran, Yu, Cheng, & Ning, 2014). These interactions can result in positive or negative effects on the perceived QoS and user's satisfaction. Considering these effects and the methodologies previously described, a structure of how pedestrians perceive their PPSI is proposed in Figure 2.1.

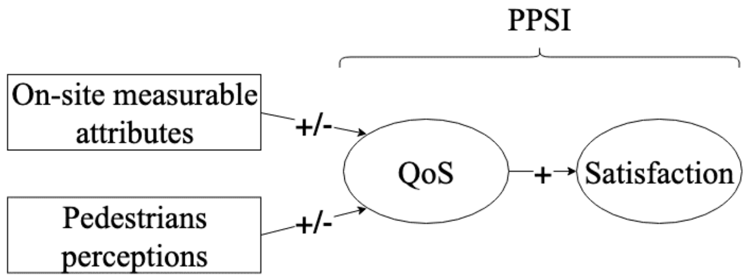

Figure 2.1. Proposed structure of pedestrians' perceived QoS

As Figure 2.1 sets out, an understanding of the perceived QoS is the base on which later understanding other effects on PPSIs is built. Pedestrian QoS can be influenced positively and negatively depending on the interaction between the pedestrian and the sidewalk. For example, there is much evidence supporting the fact that the sidewalk characteristics positively impact the pedestrians' PPSIs (e.g., sidewalk width, sidewalk condition, furniture, trees, public transport access, and signage) (Asadi-Shekari, Moeinaddini, & Zaly Shah, 2013; Banerjee, Maurya, & Lämmel, 2018). In addition, there are also surroundings characteristics like the weather (Ewing et al., 2006; Kang & Fricker, 2016; Kang et al., 2013), lighting (Jaskiewicz, 1999; Kang et al., 2013; Motamed & Bitaraf, 2016; Pikora et al., 2003), cleanliness (G. R. Bivina et al., 2018; Motamed & Bitaraf, 2016; Pikora et al., 2003), and landscape (T. Kim et al., 2011; Motamed & Bitaraf, 2016) that positively impact the pedestrians' QoS perceptions. Also, the protection that pedestrians perceive in terms of safety (Christopoulou & Pitsiava-Latinopoulou, 2012; Pikora et al., 2003) and security (G. R. Bivina et al., 2018; Gallin, 2001; Motamed & Bitaraf, 2016; Villaveces Dr. et al., 2012) positively impacts the PPSI and how pedestrians perceive the QoS. Finally, it has also been found that providing good amenities for pedestrians like public restrooms (Motamed & Bitaraf, 2016), shops (Jensen, 2007; Motamed & Bitaraf, 2016; Pikora et al., 2003), and shade (Jaskiewicz, 1999; Macdonald et al., 2018) also positively impacts their perception of QoS.

On the other hand, there are also some sidewalk attributes related to pedestrian interactions that negatively impact the different PPSIs. For example, the discomfort that pedestrians feel when they interact with other pedestrians negatively impacts the pedestrian perception of QoS (G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Sahani et al., 2017). Similarly, the effects that produce on pedestrians the motor vehicles (externalities) like the HGV flow (Mozer, 1994), vehicular speed (Christopoulou & Pitsiava-Latinopoulou, 2012; Jaskiewicz, 1999; Jensen, 2007; S. Kim et al., 2013; Landis et al., 2001; Motamed & Bitaraf, 2016; Mozer, 1994; Pikora et al., 2003; Sahani et al., 2017; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2010, 2016), noise (Christopoulou & Pitsiava-Latinopoulou, 2012; Motamed & Bitaraf, 2016; Sarkar, 2003), pollution (Motamed & Bitaraf, 2016; Pikora et al., 2003; Sarkar, 2003), and some characteristics of the vehicular transportation infrastructure like road width (Carter et al., 2013; Jensen, 2007; S. Kim et al., 2013) and the number of vehicular lanes (Carter et al., 2013; Choi et al., 2016; Jensen, 2007; Kang & Fricker, 2016; Macdonald et al., 2018; Motamed & Bitaraf, 2016; Mozer, 1994; State of Florida Department of Transportation, 2009; Transportation Research Board, 2010, 2016) also negatively impact the PPSI and the pedestrians' perception of the QoS. Finally, the interaction of pedestrians with bicyclists in terms of bicycle flow (Dandan et al., 2007; Jensen, 2007; Kang & Fricker, 2016; Kang et al., 2013; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Sahani et al., 2017) and speed (Kang & Fricker, 2016; Kang et al., 2013; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007) also negatively impacts their perception of QoS.

The different attributes affecting pedestrians' perceived PPSI have been identified from the literature review. It has been common practice to use objective and subjective attributes independently of each other to understand and calculate the different PPSI. However, there is no clear quantification of how much the users' perceptions impact the perceived QoS. In addition, there are few studies that consider pedestrian perceptions of their sensorial experience when walking to explain the pedestrian's perceived QoS. Geetha Rajendran Bivina & Parida (2019) found that there are four latent variables that positively affect the PLOS. However, latent variables that negatively impact the pedestrian perception of the QoS were not found in the literature. In addition, there are no methodologies that consider the interaction of pedestrian and the infrastructure to provide a PPSI calculation. These gaps will be addressed in this study by expanding on existing knowledge about the role of perceptions in the explanation and calculation of quality of service.

3. Methodology

The aim of this study is to examine how and to what extent the pedestrian sensorial walking experience on urban sidewalks explains pedestrian perceptions of the QoS. To fulfill it, a literature review was conducted to identify the main attributes and methodologies related to PPSI calculation and pedestrian QoS. Then, based on the literature review, 1056 interception surveys were applied in Bogotá, asking pedestrians about their perceptions of sidewalk attributes. To quantify the contribution of the perception of sidewalk attributes to the explanation of the perceived QoS, initially, OLS models were estimated by combining groups of independent variables (environmental, sociodemographic, physical, and perceptual). Then, to understand how pedestrians perceived the QoS, a QoS pedestrian cognitive map using a SEM approach was proposed. Finally, to predict the perceived QoS and sidewalk QoS (SQoS) using pedestrians' perceptions, four different approaches were used (OLS, ordered probit, continuous MIMIC, and ordered probit MIMIC), and the best one for each case was selected by considering the match score, error variability, and χ^2 values. This chapter outlines the methodology that was followed to carry out each of these processes.

3.1 Literature review process

To identify attributes that affect pedestrian QoS when walking, as well as the methodologies available for the prediction of different PPSI, a four-step literature review was developed (Figure 3.1). In step 1, four databases (Web of Science ®, SCOPUS ®, ASCE ® and EBSCOhost ®) in which relevant articles would be searched for were selected. Step 2 identified the most relevant keywords related to pedestrians and the QoS rating (pedestrian, sidewalk, level of service, quality of service, comfort, satisfaction, pleasure, and stress). These terms were combined using as a base terms "pedestrian" and "sidewalk" and adding the terms "level of service", "quality of service", "comfort", "satisfaction", "pleasure", and "stress". In step 3 the search was limited in terms of time period from 1950 to 2019 and by topic where only relevant articles related to urban sidewalks were considered. Finally, step 4 identified the different attributes and main methodologies related to PPSI and its calculation. In some cases, relevant literature was also identified within the references of each of the studied papers as well as by considering advisors' and evaluators' recommendations.

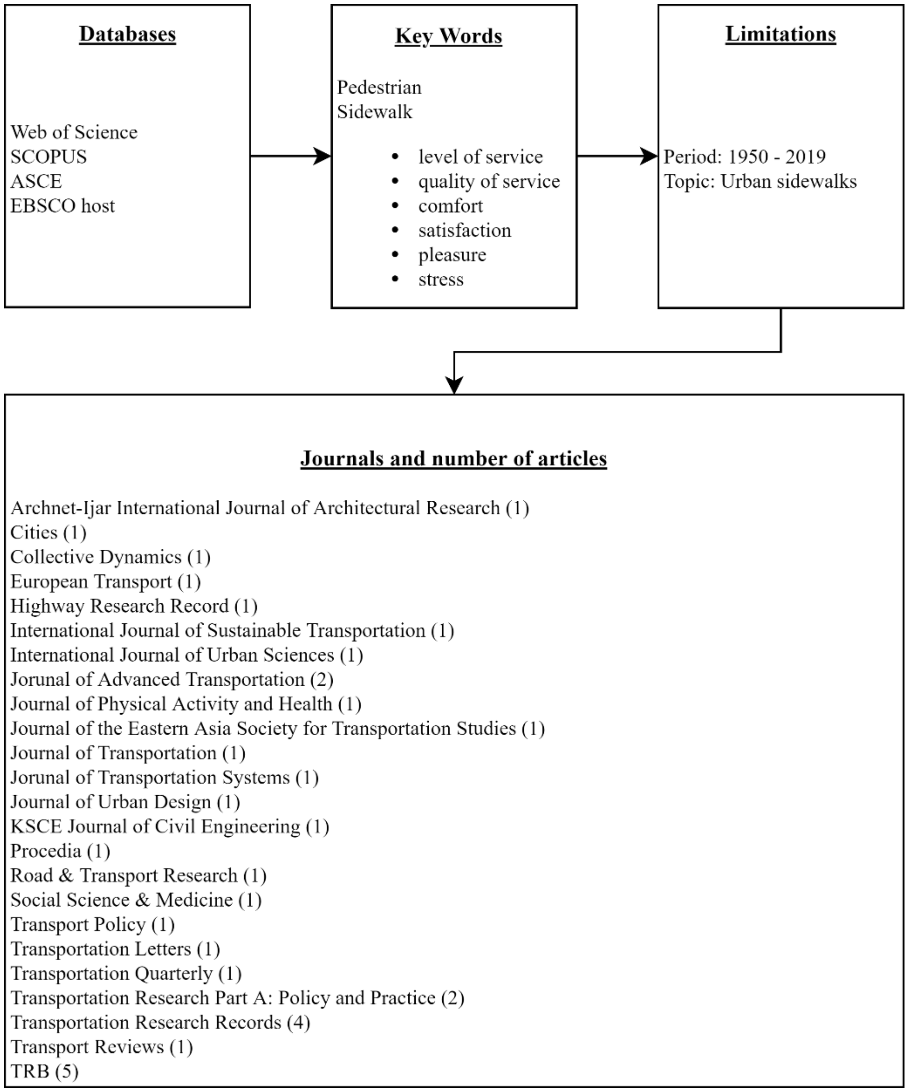

Figure 3.1. Literature Review Process

3.2 Data collection

The last origin-destination (OD) survey for Bogotá showed that 53.01% of the travelers are women, that 33.34% of the travelers are 25 years or under, and 9.71% are over 65 years old. In terms of socio-economic strata (see note in Table 3.1), approximately 10.1% of the travelers are strata 1, almost 40% are strata 2, 35.4% are strata 3, 10% are strata 4, 2.5% are strata 5, and less than 2% are strata 6. Finally, the OD survey showed that 48.11% of the travelers are employed and that 18.21% are students (Secretaría Distrital de Movilidad, 2015).

A pedestrian intercept survey was administered in 30 locations around the city of Bogotá, Colombia, covering different zones in order to attain a diverse population (see Figure 3.2). To select sidewalks were initially randomly selected 45 locations, then, were discarder the overrepresented sidewalks, and finally the sidewalks sample was completed by selecting sidewalks with characteristics under-represented. By the end, 1056 valid surveys were obtained (see Table 3.1). The number of surveys was equally distributed at each point and the survey locations were selected to include all attributes identified in the literature review. Surveys were carried out between June 2 and June 19, 2018, on working days, from 08:00 to 18:00. Each survey lasted approximately eight minutes and the overall response rate was 33.2%. Respondents were selected at random (one every three passing pedestrians).

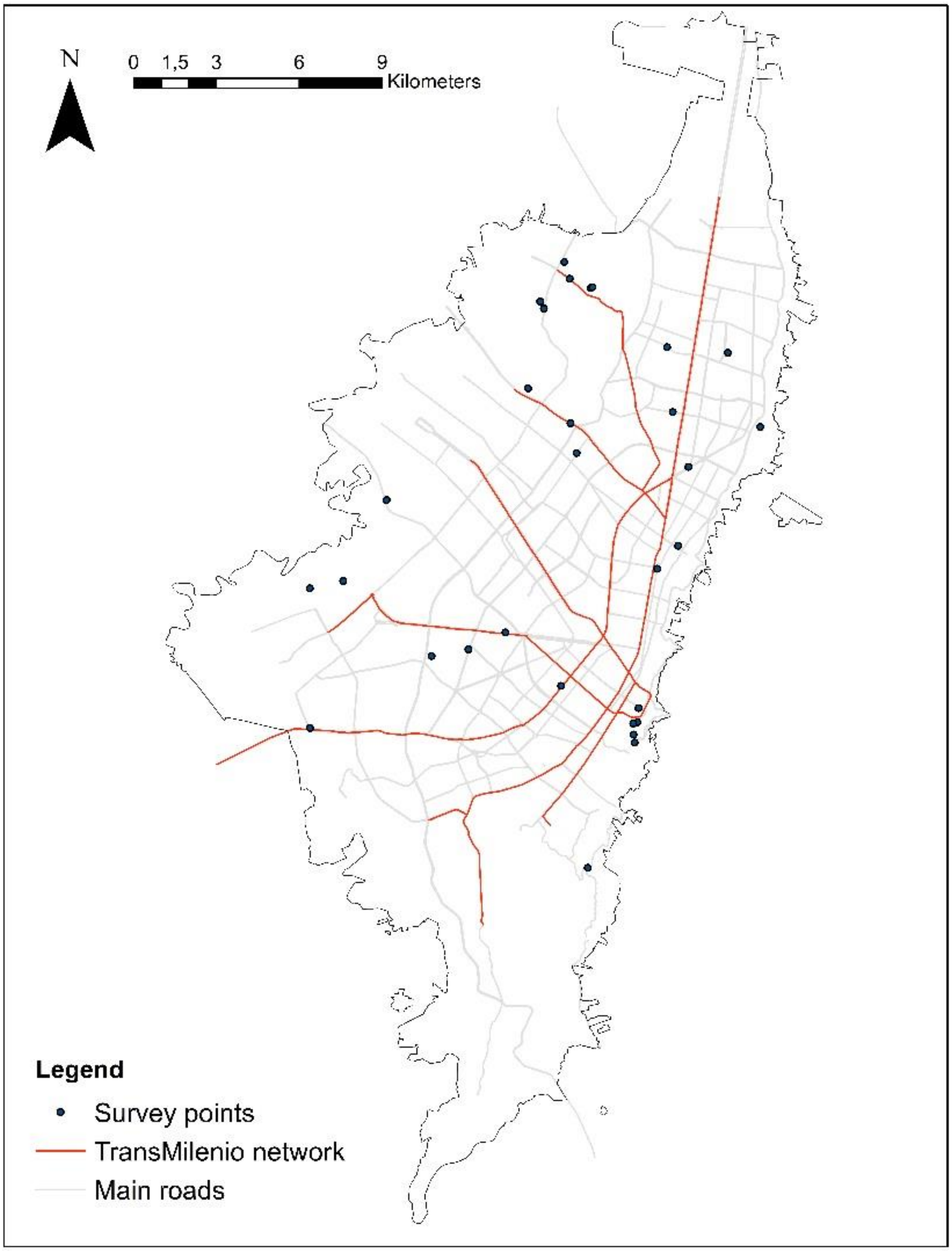

Figure 3.2. Survey points

Table 3.1. Pedestrian sample composition

Indicator	n (%)
Sex	
Female	508 (49.32)
Male	522 (50.68)
Age	
Minimum	10
First quartile	22
Median	30
Mean	34.97
Third quartile	46
Maximum	81
Socio economic strata*	
1	83 (8.34)
2	374 (37.59)
3	373 (37.49)
4	90 (9.05)
5	58 (5.83)
6	17 (1.71)
Occupation	
Employee	391 (37.52)
Student	259 (24.86)
Unemployed	69 (6.62)
Self-employed	217 (20.83)
Retired	56 (5.37)
Other	50 (4.80)
Marital status	
Single	593 (56.64)
Married	198 (18.91)
Domestic partnership	203 (19.39)
Widow(er)	14 (1.34)
Divorced	12 (1.15)
Separated	27 (2.58)

*In Colombia the socio-economic strata serve to differentiate people based on their income level, with 1 being the poorest and 6 the richest

The questionnaire asked about the overall perceived QoS of a specific sidewalk, using a 0 to 10 Likert scale (where 0 was poor and 10 excellent). In addition, the questionnaire included general perception questions (see Table 3.2) and sidewalk-related perception statements (see Table 3.3) or questions (see Table 3.4). Finally, the questionnaire also contained questions relating to the pedestrian trip and socio-demographic characteristics (see Table 3.5).

Table 3.2. General perception questions

Variable	Statement/Question	Range
Pedestrians Restrooms Shops Shade Street vendors	Rate, from 0 to 10, how comfortable would you find the general presence of the following when walking:	0 – 10
Bike flow Bike speed Opposite direction flow Same direction flow Obstructions	Rate, from 0 to 10, how bothering would you find the presence of the following when walking on the sidewalk:	

Table 3.3. Sidewalk-related statements

Variable	Statement/Question	Range
Where 0 is totally disagree and 10 totally agree, rate from 0 to 10 the following statements:		
Pedestrians far away from me	When walking on this sidewalk, I prefer other pedestrians to be far away from me	0 – 10
Stress	Walking on this sidewalk is stressful	
Too many pedestrians	On this sidewalk, the number of pedestrians does not let me walk freely	
Vehicular flow too close	On this sidewalk the motor vehicle flow is too close to me	
I prefer not to walk here	I would rather not walk on this sidewalk	
Crossing the street is easy	On this sidewalk it is easy to cross to the other side	
Accessibility	On this sidewalk it is easy to walk with a stroller or wheelchair	
Connectivity	To take today's walk I could use another route	
Order	This sidewalk is orderly	

Table 3.4. Sidewalk-related questions

Variable	Statement/Question	Range
Road width Lanes Vehicular flow HGV flow Vehicular speed Pollution Noise	Rate, from 0 to 10, how much do the following characteristics at this point of the sidewalk bother you:	0 – 10
Weather Lighting Odor Environment Cleanliness Landscape	Rate, from 0 to 10, how comfortable you feel with the following aspects at this moment and point of the sidewalk:	
Security Sidewalk safety Road safety Weather	Rate, from 0 to 10, how protected you feel at this time regarding the following aspects at this point on the sidewalk:	
Width Condition Furniture Trees Facades Public transport access Signage	Where 0 is poor and 10 excellent, rate from 0 to 10 this point on the sidewalk in relation to the following:	

Table 3.5. Questions about pedestrian trip and sociodemographic characteristics

Variable	Statement/Question
Group	How many people are with the respondent?
Origin	Where are you walking from?
Destination	Where are you walking to?
Duration	How long will this walk take?
Frequency	Is this walk frequent?
Sex	male = 0; female = 1
Age	[Years]
Occupation	employee = 1; student = 2; unemployed = 3; self-employed = 4; retired = 5; other = 6
Marital status	single = 1; married = 2; domestic partnership = 3; widow(er) = 4; divorced = 5; separated = 6; other = 7
Household size	[Number]
Socioeconomic status	[Number]

Sampling was based on three different techniques (power calculation, central limit theorem, and sample size recommendations for latent variables), and was designed to identify differences between the categories of some sidewalk attributes. Initially, the sidewalk attribute categories were established following the literature (Table 3.6). Then, the maximum number of categories required to carry out the sampling without considering the number of sidewalks was identified.

Table 3.6. Categories of sidewalk attributes

Attribute	(Author, year)	1	2	3	4	5
Sidewalk width	(Gallin, 2001)	[0, 1] m	(1, 1.5] m	(1.5, 2] m	(2, ∞) m	
Sidewalk width	(Muraleetharan et al, 2005)	[0, 1.5] m	(1.5, 3] m	(3, ∞) m		
Sidewalk width	(Christopoulou & Pitsiava-Latinopoulou, 2012)	[0, 1.5] m	(1.5, 2.2] m	(2.2, ∞) m		
Sidewalk width	(Muraleetharan & Hagiwara, 2007)	[0, 1.5] m	(1.5, 3] m	(3, ∞) m		
Sidewalk width	(Talavera-Garcia & Soria-Lara, 2015)	[0, 0.9) m	[0.9, 1.5) m	[1.5, 2.25) m	[2.25, 3) m	[3, ∞) m
Trees – density	(Talavera-Garcia & Soria-Lara, 2015)	[0, 5000) t/km^2	[5000, 10000) t/km^2	[10000, 15000) t/km2	[15000, 20000) t/km^2	[20000, ∞) t/km^2
Buffer	(Landis et al, 2001)	No buffer	No elements	Elements	Vehicles	
Vehicular lanes	(Talavera-Garcia & Soria-Lara, 2015)	3	2	1		
Conflicts	(Gallin, 2001)	(25, ∞) conflicts/km	(15, 25] conflicts/km	(10, 15] conflicts/km	(0, 10] conflicts/km	0
Conflicts	(Christopoulou & Pitsiava-Latinopoulou, 2012)	[0, 100) m	[100, 200) m	[200, ∞) m		
Tree presence	-	Yes	no			
Restroom presence	-	Yes	no			
Buffer presence	-	Yes	no			
Cycle infrastructure presence	-	Yes	no			
Bus stop presence	-	Yes	no			
Median Strip presence	-	Yes	no			
Land use	-	Institutional	Commercial and services	Industry	Residential	Other

To calculate the sample size using the power calculation, the following elements are required: the effect size (d), significance level or type I error probability (sig. level), and the power (1 minus type II error probability). For this study, a sig. level of 0.05, a power of 0.80, and an effect size of 0.30 (obtained from previous surveys) were established. The R function “pwr.t.test” from the package “pwr” (Champely, 2018; R Core Team, 2019) was used to calculate the sample size. The analysis using this technique recommended a sample size of 176 responses per category. Considering that the maximum number of categories is 5 (see Table 3.6) and that 176 responses were needed per category, the power calculation defined a sample size of 880 individuals.

Using another technique, according to the central limit theorem (Walpole, Myers, Myers, & Ye, 2012), 30 surveys are required per point to obtain a normally distributed SQoS mean. Similarly, considering that this study aims to compare the performance of 28 methodologies for calculating PPSI, it was decided that the surveys should be carried out on 30 different sidewalks (see Figure 3.2). For this reason, the central limit theorem technique would recommend a sample size of 900 respondents (30 surveys per sidewalk on 30 different sidewalks). However, as the use of a security factor is recommended, the decision was made to administer five additional surveys on each sidewalk, generating a sample size of 1050 surveys.

Finally, using the sample size recommendations for studies that use latent variables in a conservative way, the decision was made to use a sample size of 20 times the number of variables (Mundfrom, Shaw, & Ke, 2005). As there are 43 independent variables in the questionnaire (see Table 3.2, Table 3.3, and Table 3.4) a sample size of 860 was calculated. In spite that the three techniques previously mentioned are used to meet different needs (e.g., power analysis to have enough power to detect associations, central limit theorem to have enough power to make inferences about the population mean), a sample size of 1050 respondents was chosen, using the result of the central limit theorem technique as it produced the largest sample size.

Sidewalk selection made sure to cover all previously identified categories (see Table 3.6). Initially, 45 random locations in Bogotá were selected. Then, each one was visited and sidewalk information was collected about the objective on-site attributes identified in the pedestrian QoS literature (see Table 3.7). From this data collection process, sidewalks comprising a variety of attributes were selected and sidewalk that overrepresent the characteristics were discarded. Then, sidewalks with characteristics that were not present in the initially selected sidewalks were chosen to complete the sample of 30 sidewalks. The different characteristics and a sample image of each sidewalk can be seen in Appendix A – Sidewalk sample.

Table 3.7. Sidewalk on-site measurable attributes

Attribute	Units	Attribute	Units
Sidewalk width	[m]	Lanes width	[m]
Sidewalk length	[m]	Road width	[m]
Trees	[Number]	Shoulder width	[m]
Lanes	[Number]	Bicycle infrastructure width	[m]
Conflicts	[Number]	Driveway length	[m]
Restrooms	[Number]	Transparent panel length	[m]
Median strip	[yes=1; no=0]	Roof length	[m]
Buffer width	[m]	Sidewalk entrances	[Number]
Buffer presence	[yes=1; no=0]	Driveways	[Number]
Land use	[see Table 3.6]	Ramps	[Number]
Speed limit	[km/h]	Facade separation	[m]
Exterior lane width	[m]		

Once the 30 sidewalks were selected, a team visited them to collect all the data needed. The team was composed of four surveyors and one technician who worked eight hours per day during working days. On each sidewalk, specific assignments were assigned to each member of the team to collect the data required by the survey (see Table 3.2, Table 3.3, Table 3.4, and Table 3.5) and also the objective on-site variable attributes (see Table 3.8).

Table 3.8. Sidewalk on-site variable attributes

Attribute	Period/Units	Attribute	Period/Units
Bicycle flow on road	[5 min]	Other flow on sidewalk	[5 min]
Motorcycle flow	[5 min]	Vehicular speed	[km/h]
Vehicular flow	[5 min]	Noise	[dB]
Bus flow	[5 min]	Temperature	[°C]
HGV flow	[5 min]	Lighting	[lux]
Pedestrian flow	[5 min]	Humidity	[% Hr]
Bicycle flow on sidewalk	[5 min]	On-street parking	[Number]

3.3 Modelling approach

Five different models were considered in the specification searches of this study. OLS and ordered probit models are a common choice to study the influence of independent variables on a specific dependent variable (which for this study is the perceived QoS). Structural equation models (SEM) and multiple indicator and multiple cause (MIMIC) models are commonly used to test the existence of latent variables from perception attributes that, in the case of MIMIC models, can be forecasted or explained by objective attributes. Finally, the multi-attribute utility theory (MAUT) is normally used to define a ranking by comparing the results of certain characteristics of different options.

3.3.1. Ordinary least squares (OLS) models

The OLS model presented in Equation (1) is used to quantify the contribution of perception attributes to the explanation of perceived QoS. In addition, this model is one of the options for the proposition of a forecasting model of the perceived SQoS and QoS. It is commonly used for its simplicity in estimating a linear equation to explain a dependent variable (y) on the basis of a set of independent variables (x_i). OLS models assume independence between the independent variables and homoscedasticity (Ortúzar & Willumsen, 2011, Section 4.2.1).

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i * x_i + \varepsilon \qquad (1)$$

The OLS models can quantify the proportion of variation in the data explained by the model. In fact, the coefficient of determination (R^2) is defined as the ratio between the explained variation and the total variation (Ortúzar & Willumsen, 2011, page 150), and can be calculated using Equation (2):

$$R^2 = \frac{\sum_{i=1}^{n}\left(\hat{Y}_i - \bar{Y}\right)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \qquad (2)$$

The R^2 value increases with the inclusion of more independent variables. For this reason, the adjusted R^2 was developed to correct for this problem. The adjusted R^2 can be calculated using Equation (3):

$$adj\ R^2 = \left(R^2 - \frac{k}{n-1}\right) * \left(\frac{n-1}{n-k-1}\right) \quad (3)$$

where *n* is the sample size and *k* the number of independent variables.

In addition, to test if all coefficients of the OLS models are significantly different from zero, an F-test was calculated for the complete model. Using this test, the null hypothesis (H_0) poses that all coefficients are equal to 0 ($H_0: (\beta_0, \beta_i) = 0$). In this case, H_0 is accepted if the F-test value is less than or equal to the F critical value (Ortúzar & Willumsen, 2011, page 151).

3.3.2. Ordered probit models

Ordered probit models are an appropriate approach for choice modeling with discrete and ordered nature data (Harvey & Amemiya, 2006; Washington, Karlaftis, & Mannering, 2010). To use this model, an unobserved variable *z* is defined usually as a linear function of each observation: (see Equation (4))

$$z = \beta X + \varepsilon \quad (4)$$

where *X* is a vector of variables determining the observations' order, β a vector of parameters, and ε a random disturbance. This model assumes that all parameters β are the same for the different ordered categories. Using Equation (4), the observed ordered data (*y*) for each observation is defined by taking Equation (5) into consideration (Washington et al., 2010).

$$\begin{array}{lll} y = 1 & if & z \leq \mu_0 \\ y = 2 & if & \mu_0 < z \leq \mu_1 \\ y = 3 & if & \mu_1 < z \leq \mu_2 \\ y = \cdots & & \\ y = I & if & z \geq \mu_{I-1} \end{array} \quad (5)$$

where μ_i are estimated thresholds that define *y*, and "*I*" is the highest integer ordered response. If the random disturbance is assumed to be independent and normally distributed with mean 0 and variance 1, the probabilities for the ordered probit model can be calculated using Equation (6):

$$P(y=1)=\Phi(-\beta X)$$

$$P(y=2)=\Phi(\mu_1-\beta X)-\Phi(-\beta X)$$

$$P(y=3)=\Phi(\mu_2-\beta X)-\Phi(\mu_1-\beta X) \quad (6)$$

$$P(y=I)=1-\Phi(\mu_{I-1}-\beta X)$$

Where $\Phi(*)$ is the cumulative normal distribution that can be calculated using Equation (7):

$$\Phi(\mu)=\frac{1}{\sqrt[2]{2\pi}}\int_{-\infty}^{u} EXP\left[-\frac{1}{2}w^2\right]dw \quad (7)$$

3.3.3. Structural equation modeling (SEM)

This methodological approach has been applied in the past in transportation studies of airports (Bezerra & Gomes, 2016), pedestrian infrastructure (Geetha Rajendran Bivina & Parida, 2019; Cantillo, Arellana, & Rolong, 2015), and public transport satisfaction (Eboli & Mazzulla, 2015) to name a few. SEM is a statistical modeling tool that can be used as an extension of linear models (Lei & Wu, 2007). Notation in SEM can be defined as follows:

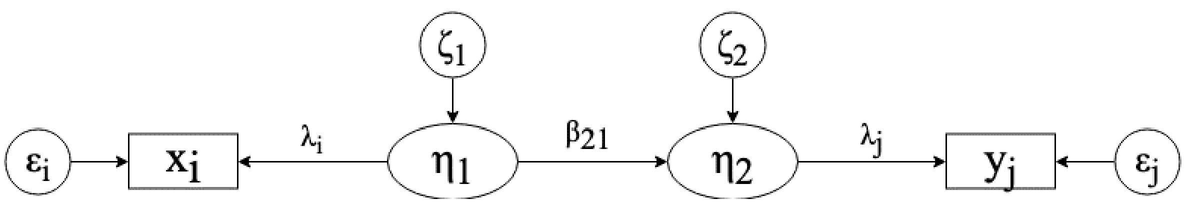

Figure 3.3. SEM generic model structure

$$y_j=\alpha_j+\lambda_j\eta_2+\varepsilon_j \quad (8)$$

$$x_i=\alpha_i+\lambda_i\eta_1+\varepsilon_i \quad (9)$$

$$\eta_2=\beta_{21}\eta_1+\zeta_2 \quad (10)$$

Figure 3.3 represents a generic model with two latent variables (η_1 and η_2), and *i* and *j* common-factors or indicators (*x* and *y*). The indicators are measured from subjective attributes (e.g., perceptions) and are a function of two variables, where one of them is common to all (η_1 or η_2) and can be calculated using Equations (8) and (9), where α is the intercept term (constant), λ coefficients indicate the change in the value of the observed attributes if there is a change of one unit in the latent variable, and ε is the error in the measurement equation for *x* or *y* with an expected value of zero. Additionally, latent variable η_2 is a function of latent variable η_1 and can be calculated using Equation (10), where the β coefficient is the structural parameter that indicates the change in the value of η_2 if there is a change of one unit in η_1; ζ_2 is the random error for the latent variable with a mean expected value of zero. For this study, the errors were assumed to be distributed normally. To test the generic model, all assumed relationships were considered simultaneously, and the complete model fit was evaluated to assure that the estimated covariance matrix was significant and similar to the observed covariance (Lei & Wu, 2007; McDonald & Bollen, 2006).

3.3.4. Multiple indicator multiple cause (MIMIC) models

MIMIC is another methodology that is used in this study to propose a forecasting model for the perceived SQoS and QoS. MIMIC is an extension of SEM models and can be developed using continuous, ordinal, and discrete variables. Figure 3.4 presents, on the left, where the MIMIC dependent variable is a continuous variable and, on the right, where the MIMIC dependent variable is ordinal or discrete.

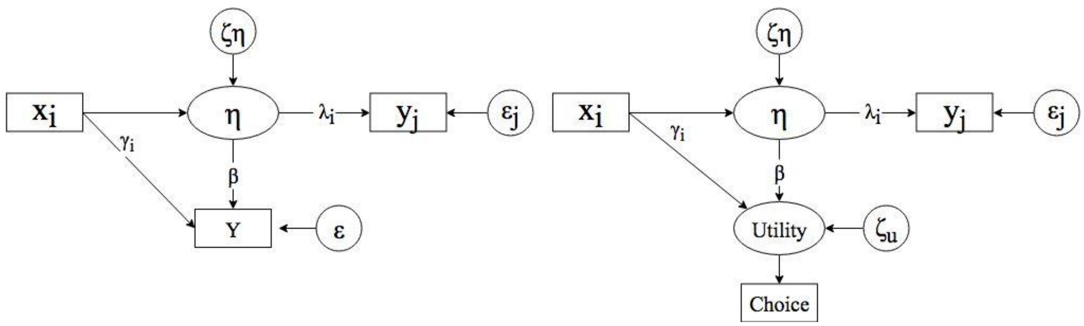

Figure 3.4. Continuous, ordered, and discrete MIMIC general models

Figure 3.4 represents a generic model with one latent variable (*η*), *j* represents common-factors or indicators (*y*), and *i* attributes or independent variables (*x*). The common-factors are measured from subjective attributes (e.g., perceptions) and are a function of two variables, where one of them is common to all (*η*) and can be calculated using Equation (11), where α represents the intercept term (constant), λ coefficients indicate the change in the value of the observed attributes if there is a change of one unit in the latent variable, and ε is the error in the measurement equation with an expected value of zero. Additionally, latent variable *η* is a function of the objective attributes (x_i) used as independent variables and can be calculated using Equation (12), where the γ coefficient is the structural parameter that indicates the change in the value of *η* if there is a change in one unit in *x*, and ζ_η is the random error for the latent variable with a mean expected value of zero. Similarly, the dependent variable (*Y*) is a function of the independent variables (x_i) and the latent variable (*η*) and can be calculated using Equation (13), where the γ coefficient is the structural parameter that indicates the change in the value of *Y* if there is a change in one unit in *x*, the β coefficient is the structural parameter that indicates the change in the value of *Y* if there is a change in one unit in *η*, and ε is the random error for the dependent variable with a mean expected value of zero. For this study, the errors were assumed to be distributed normally. To test the generic model, all the assumed relationships are considered at the same time, and the complete model is fit evaluated to assure that the estimated covariance matrix is significant and similar to the observed covariance (Lei & Wu, 2007).

$$y_j = \alpha_j + \lambda_j \eta + \varepsilon_j \quad (11)$$

$$\eta = \gamma_i x_i + \zeta_\eta \quad (12)$$

$$Y = \gamma_i x_i + \beta \eta + \varepsilon \quad (13)$$

Forecasting using MIMIC requires estimating a complete model composed by the measurement model and the structural model (attributes and indicators). For this reason, to build a forecasting model the following steps were carried out:

1. The development of the best fit SEM model using only perception attributes (measurement and structural model)
2. The prediction of the dependent variable (service quality) and all latent variables of the best fit model using on-site measurables attributes
3. The inclusion of the on-site measurable attributes with a p-value lower than 0.10 using a forward iteration approach (introducing the attributes with a lower p-value and greater t-statistic first)

3.3.5. Multi-attribute utility theory (MAUT)

The multi-attribute utility theory is a methodology developed for selecting the best option (for this study the best model) by considering diverse objectives simultaneously (adj R^2 and F value). This methodology is highly recommended for use with quantitative data (Hernández, 2006) and can be applied using Equation (14):

$$u_i(x) = \frac{x - worst\ value}{best\ value - worse\ value} \quad (14)$$

where *u* is the utility defined for each attribute value *x*.

3.4 Performance indicators

The match score was defined as one of the performance indicators for testing the methodologies' and models' performance. To decide whether there is a match or not, the boundaries (upper and lower limit) of the expected value are calculated first. Then, a score of 1 is assigned to the cases where the obtained value is within the boundaries. In addition, the error variability is considered using the differences between the obtained value and the expected value for each case. Using the differences, the minimum and maximum value, and the first, second, and third quartile are calculated to visualize the error variability. These differences are shown in box plots that consider the interquartile range of differences. With the different box plots it is possible to easily identify outliers, as well as the first, second, and third quartiles. The box plots were developed using the function "boxplot" of R (R Core Team, 2019).

Similarly, the χ^2 test is used to determine if the observed data distribution and the predicted data distribution are not significantly different (null hypothesis). This test compares the expected (E) and observed (O) totals for each defined category (Ortúzar &

Willumsen, 2011, page 287). This comparison is done through the calculation of the χ^2 statistic using Equation (15):

$$\chi^2 = \sum_{i=1}^{m} \frac{(O_i - E_i)^2}{E_i} \tag{15}$$

where m is the number of categories, and χ^2 must be compared with the critical value ${\chi^2}_{0.95}$ with m-1 degrees of freedom. If $\chi^2 < {\chi^2}_{0.95;m-1}$ the null hypothesis is consistent and accepted (Ortúzar & Willumsen, 2011).

3.5 Methodological performance evaluation process

The methodological performance process was developed to quantify the local representation of different PPSI calculation methodologies in Bogotá. The first step was to identify the different PPSI calculation methodologies proposed in the literature where was identified 28 different methodologies. Then, a summary of each methodology was elaborated (see Appendix B – Methodological review) to compare the results of the methodologies with the SQoS perceived by pedestrians.

The 28 methodologies were initially coded to facilitate the presentation of results, as shown in Table 3.9. The methodologies were compared considering the match score and the error variability. A score of 1 was assigned to the methodologies that matched the users' perceived SQoS of each sidewalk. For the cases that methodologies rated the service provided for a sidewalk assigning a letter, the boundaries were estimated dividing the likert scale used for the surveys (0 to 10) in the number of categories (letters) proposed for the methodology. For the cases that methodologies rated this service in a numerical scale, the boundaries were estimated using a 95% confidence interval of the SQoS. The results of the match score are presented as a percentage value, representing the number of sidewalks that each methodology predicted correctly out of the 30 sidewalks. In addition, the errors were computed as the difference between the forecasted PPSI value (by each methodology) and the pedestrians' QoS perception (see 3.4 Performance indicators). The error dispersion is shown in box plots that consider the interquartile range of differences.

Table 3.9. Abbreviation of the different PPSI methodologies

Abbr.	Authors	Abbr.	Authors
Me 01	(Fruin, 1971)	Me 15	(Dandan et al., 2007)
Me 02	(Polus et al., 1983)	Me 16	(Muraleetharan & Hagiwara, 2007)
Me 03	(Transportation Research Board, 1985)	Me 17	(State of Florida Department of Transportation, 2009)
Me 04	(Mōri & Tsukaguchi, 1987)	Me 18	(Transportation Research Board, 2010)
Me 05	(Tanaboriboon & Guyano, 1989)	Me 19	(Christopoulou & Pitsiava-Latinopoulou, 2012)
Me 06	(Mozer, 1994)	Me 20	(S. Kim et al., 2013)
Me 07	(Jaskiewicz, 1999)	Me 21	(S. S. Kim et al., 2014)
Me 08	(Transportation Research Board, 2000)	Me 22	(Talavera-Garcia & Soria-Lara, 2015)
Me 09	(Gallin, 2001)	Me 23	(Transportation Research Board, 2016)
Me 10	(Landis et al., 2001)	Me 24	(Choi et al., 2016)
Me 11	(Alcaldia Mayor de Bogota D.C., 2005)	Me 25	(Marisamynathan & Lakshmi, 2016)
Me 12	(Muraleetharan et al., 2005)	Me 26	(Sahani et al., 2017)
Me 13	(Petritsch et al., 2006)	Me 27	(Macdonald et al., 2018)
Me 14	(Jensen, 2007)	Me 28	(G. R. Bivina et al., 2018)

3.6 Determining how and to what extent perceptions influence the perceived QoS

To quantify the influence of pedestrian's perceptions on the explanation of the perceived QoS, 15 different models were created that include four categories of independent variables (environmental, sociodemographic, physical, and perceptual). The 15 different models combined the different categories of independent variables into groups that contained 1, 2, 3, and all 4 categories in each model (see Table 3.10).

Table 3.10. Proposed models to explore the contribution of perception in the QoS

Model	Environment	Sociodemographic	Physical	Perception
M1	✓			
M2		✓		
M3			✓	
M4				✓
M5	✓	✓		
M6	✓		✓	
M7	✓			✓
M8		✓	✓	
M9		✓		✓
M10			✓	✓
M11	✓	✓	✓	
M12	✓	✓		✓
M13	✓		✓	✓
M14		✓	✓	✓
M15	✓	✓	✓	✓

Once the 15 different models were developed, an OLS modeling approach was estimated to quantify three different goodness of fit indicators (partial R^2, adjusted R^2, and F-value of the regression, see 3.3.1 Ordinary least squares (OLS) models above). For the partial R^2, a combination of each model was developed to quantify the explanation boundaries of the perceived QoS of each considered category using the R function "eta_sq" of the "sjstats" package (Lüdecke, 2019; R Core Team, 2019). This combination is needed because the order in which categories are added into the model affects the contribution to the variance explained by each category. In the other cases, the adjusted R^2 and the F-value of the regression were calculated for each model using the R function “lm” (R Core Team, 2019), and were compared using the multi-attribute utility theory (MAUT) (see 3.3.5 Multi-attribute utility theory (MAUT) above).

In addition, a cognitive map was proposed and constructed from pedestrian perceptions (Table 3.2, Table 3.3, and Table 3.4) using a structural equation modelling (SEM) approach (see 3.3.3 Structural equation modeling (SEM) above) to explain the way that QoS is perceived by pedestrians. This process was developed using the R function “sem” of the “lavaan” package (R Core Team, 2019; Rosseel, 2012).

3.7 Forecasting the perceived QoS

To propose a forecasting model, four different approaches were used: 1) OLS (see 3.3.1 Ordinary least squares (OLS) models above), 2) ordered probit (see 3.3.2 Ordered probit models above), 3) continuous MIMIC (see 3.3.4 Multiple indicator multiple cause (MIMIC) models above), and 4) ordered probit MIMIC (see 3.3.4 Multiple indicator multiple cause (MIMIC) models above). Initially, the dataset was divided into two parts: 70% to estimate the models, and 30% to validate them (Ortúzar & Willumsen, 2011, section 8.4.1.6). Then, once the different forecasting models were estimated, their performance was compared using the match score, error variability, and an χ^2 test (see 3.4 Performance indicators above). In this case, the boundaries needed to apply the match score were estimated using a 95% confidence interval of the SQoS. Through these comparisons, different forecasting models were proposed for the calculation of the SQoS and the QoS to be applied in Bogotá. The OLS model was estimated using the R function “lm” (R Core Team, 2019), the ordered probit model using the R function “polr”, both included in the package “MASS” (R Core Team, 2019; Venables & Ripley, 2002), and the MIMIC models using the R function “sem” of the package “lavaan” (R Core Team, 2019; Rosseel, 2012).

3.8 Study limitations

This study is not going to consider some topics due to time constraints. Initially, this study is not going to deep on the impacts that can be generated because of the use of different terms to evaluate the PPSI (e.g., satisfaction, comfort). In addition, this study is going to present different methodologies to be used on the city of Bogota, however this study is not going to propose a calibration method that can be applied to use the methodologies in a different place. Finally, this study is not going to consider heterogeneous effects, and pedestrians are going to be understand as a transportation mode without considering the differences between them (e.g., sex, occupation).

4. Performance of the PPSI methodologies in Bogotá's urban context

Different groups of inputs (see Table 4.1) were taken from methods used to forecast the pedestrian performance or service indicators (PPSI) worldwide (see Appendix B – Methodological review). We found that the methodologies based on expert judgement best represented Bogotá's local conditions. Following these, the methodologies based on on-site objective attributes provide a fairly good representation. Finally, the methodologies based on the flow-capacity relationship had the lowest capability to evaluate Bogotá's local conditions.

Table 4.1. Inputs of different PPSI calculation methodologies

Input	Authors
Flow-capacity	(Alcaldia Mayor de Bogota D.C., 2005; Fruin, 1971; S. S. Kim et al., 2014; Mōri & Tsukaguchi, 1987; Polus et al., 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985, 2000)
Objective attributes	(Choi et al., 2016; Dandan et al., 2007; Jensen, 2007; S. Kim et al., 2013; Landis et al., 2001; Mozer, 1994; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Petritsch et al., 2006; Sahani et al., 2017; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2010, 2016)
Subjective attributes	(G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999; Macdonald et al., 2018; Marisamynathan & Lakshmi, 2016)

In Table 4.2, we present the results obtained for the perceived QoS in the 30 different sidewalks.

Table 4.2. Descriptive statistics of the perceived QoS per location

Segment	Perceived QoS mean	Perceived QoS SD	Perceived QoS median	Perceived QoS min.	Perceived QoS max.
1	7.171	2.455	8	2	10
2	6.629	2.777	8	0	10
3	7.314	2.541	8	0	10
4	6.771	2.237	7	2	10
5	4.800	2.194	5	0	10
6	5.378	3.616	6	0	10
7	6.686	2.153	7	2	10
8	7.486	1.931	8	4	10
9	7.286	1.949	8	2	10
10	3.361	2.685	3	0	10
11	6.200	2.805	6	0	10
12	7.371	2.365	8	0	10
13	7.694	1.939	8	3	10
14	8.056	2.254	9	2	10
15	5.571	2.913	5	0	10
16	6.714	2.444	7	0	10
17	4.714	2.793	5	0	10
18	5.543	2.214	5	0	10
19	6.171	2.770	6	0	10
20	4.000	1.940	4	0	8
21	7.000	2.288	6	2	10
22	8.229	2.197	9	2	10
23	6.914	2.466	7	2	10
24	7.457	1.615	7	3	10
25	7.000	2.262	7	0	10
26	5.743	2.201	6	0	10
27	6.771	2.636	8	0	10
28	4.914	2.822	4	0	10
29	8.429	1.929	9	3	10
30	5.389	2.780	5	0	10

Table 4.3 presents the evaluation of the 28 different PPSI methodologies for the 30 locations. In general, most of the sidewalks obtained a good sidewalk QoS (SQoS) score from the users and only two of them scored below or equal to 4.0 (locations 10 and 20). The scales of each methodology can be seen in Appendix B – Methodological review.

Table 4.3. PPSI results per methodology

Segment	Me 01	Me 02	Me 03	Me 04	Me 05	Me 06	Me 07	Me 08	Me 09	Me 10
1	A	A	A	A	A	C	C	A	C	B
2	A	A	A	A	A	D	C	A	C	B
3	A	A	A	A	A	C	B	A	C	B
4	A	A	A	A	A	C	C	A	C	B
5	A	A	A	C	A	C	D	C	C	B
6	A	A	A	A	A	D	C	A	C	B
7	A	A	A	A	A	C	D	A	C	B
8	A	A	A	A	A	D	B	A	C	C
9	A	A	A	A	A	D	B	A	C	B
10	A	A	A	A	A	D	E	A	D	C
11	A	A	A	A	A	C	C	A	C	B
12	A	A	A	A	A	D	C	A	C	D
13	A	A	A	A	A	C	C	A	B	B
14	A	A	A	A	A	D	D	A	C	C
15	A	A	A	A	A	C	D	A	D	B
16	A	A	A	A	A	D	C	A	C	B
17	A	A	A	A	A	C	D	A	C	B
18	A	A	A	A	A	D	D	A	C	B
19	A	A	A	A	A	C	C	A	C	B
20	A	A	A	A	A	D	D	A	D	C
21	A	A	A	A	A	C	D	A	C	B
22	A	A	A	A	A	C	B	A	B	B
23	A	A	A	A	A	C	C	A	C	B
24	A	A	A	A	A	D	B	A	C	B
25	A	A	A	A	A	C	B	A	C	B
26	A	A	A	A	A	C	D	A	C	B
27	A	A	A	A	A	D	B	A	C	C
28	A	A	A	A	A	C	D	A	C	B
29	A	A	A	A	A	C	B	A	C	B
30	A	A	A	A	A	D	D	A	C	B

Table 4.3 (continued). PPSI results per methodology

Segment	Me 11	Me 12	Me 13	Me 14	Me 15	Me 16	Me 17	Me 18	Me 19	Me 20
1	B	8.307	F	VS	F	4.876	B	B	B	D
2	A	9.363	B	VS	F	5.577	C	A	C	E
3	A	8.307	C	VS	A	4.876	C	A	C	A
4	B	8.674	D	VS	A	5.120	C	A	C	B
5	B	5.812	D	VS	A	3.220	B	C	C	B
6	B	6.300	E	VS	F	3.544	D	D	C	D
7	B	8.674	E	VS	C	5.120	B	B	B	D
8	A	6.300	F	VS	F	3.544	C	F	B	F
9	A	5.122	E	VS	A	2.763	D	C	B	C
10	B	6.161	C	MS	F	3.452	C	D	E	F
11	A	8.674	C	VS	A	5.120	C	A	B	B
12	A	6.867	F	VS	F	3.921	F	C	B	F
13	B	9.363	C	VS	A	5.577	B	C	C	D
14	A	8.674	F	VS	F	5.120	F	D	C	F
15	A	6.850	B	VS	A	3.909	B	B	D	C
16	A	6.867	E	VS	A	3.921	D	B	B	C
17	A	6.161	B	MS	A	3.452	B	B	D	B
18	A	8.674	B	VS	F	5.120	B	A	D	D
19	B	7.618	B	VS	A	4.419	C	A	B	A
20	B	6.161	C	MS	F	3.452	C	D	E	F
21	A	8.307	B	VS	A	4.876	B	A	B	A
22	B	9.363	C	VS	A	5.577	C	A	B	A
23	B	7.618	C	VS	A	4.419	C	B	C	B
24	B	6.178	E	VS	F	3.463	B	D	C	E
25	A	7.618	D	VS	D	4.419	B	B	C	C
26	A	6.161	B	MS	A	3.452	C	B	D	C
27	A	7.618	D	VS	F	4.419	E	C	C	F
28	A	6.850	B	VS	A	3.909	C	B	D	C
29	A	6.667	D	VS	A	3.788	D	A	B	B
30	B	7.618	B	VS	F	4.419	B	A	D	D

Table 4.3 (continued). PPSI results per methodology

Segment	Me 21	Me 22	Me 23	Me 24	Me 25	Me 26	Me 27	Me 28
1	A	B	C	Unsatisfied	E	F	C	B
2	A	C	B	Unsatisfied	A	C	F	B
3	A	B	B	Unsatisfied	D	B	B	C
4	A	B	B	Unsatisfied	C	F	A	C
5	A	B	C	Unsatisfied	E	F	F	C
6	A	B	D	Unsatisfied	E	F	A	C
7	A	C	C	Unsatisfied	D	F	D	B
8	A	C	E	Unsatisfied	E	F	A	B
9	A	B	C	Unsatisfied	D	C	A	C
10	A	C	D	Unsatisfied	E	F	F	C
11	A	C	B	Unsatisfied	C	D	D	C
12	A	C	C	Unsatisfied	E	D	A	D
13	A	C	C	Unsatisfied	C	F	F	C
14	A	B	D	Unsatisfied	E	F	B	D
15	A	C	C	Unsatisfied	C	B	F	C
16	A	B	B	Unsatisfied	D	E	C	C
17	A	C	C	Unsatisfied	D	C	F	C
18	A	C	B	Unsatisfied	B	E	F	C
19	A	B	B	Unsatisfied	C	F	A	C
20	A	C	D	Unsatisfied	E	F	F	C
21	A	C	B	Unsatisfied	C	F	C	C
22	A	B	B	Unsatisfied	C	F	A	B
23	A	B	C	Unsatisfied	E	D	B	B
24	A	C	D	Unsatisfied	D	F	B	B
25	A	B	B	Unsatisfied	D	B	C	C
26	A	C	C	Unsatisfied	C	A	F	B
27	A	C	C	Unsatisfied	D	D	A	C
28	A	C	C	Unsatisfied	C	D	F	C
29	A	B	A	Unsatisfied	D	B	B	C
30	A	C	B	Unsatisfied	C	F	F	D

The first methodologies proposed (Me 1 to Me 5) rate the sidewalks higher than the users' perception score (see Table 4.2 and Table 4.3). In addition, in the case of Bogotá, these methodologies do not vary in terms of sidewalk score; they grade all sidewalks with the best score. However, this tendency changes when other attributes - not only related to the flow-capacity relationship - are considered (see Table 4.3).

The results presented in Table 4.3 were compared with the results presented in Table 4.2 for each sidewalk in order to obtain the performance methodologies for Bogotá. A score of 1 was assigned to the methodologies that matched the user's perceptions of each sidewalk. In the cases where the methodologies considered a categorical output, the 0 to 10 scale considered for the surveys was divided in the number of categories of each methodology, as has been done in the past for similar studies (Hasan et al., 2015). All sidewalks were rated using this method and the match score results are presented in Table 4.4. The methodologies in Table 4.4 are presented in chronological order.

Table 4.4. Match score of PPSI results with users' perceived QoS

Abbr.	Authors	Score (out of 30)	Segment match [%]
Me 1	(Fruin, 1971)	1	3.33%
Me 2	(Polus, Schofer, & Ushpiz, 1983)	3	10.00%
Me 3	(HCM, 1985)	1	3.33%
Me 4	(Mori & Tsukaguchi, 1987)	5	16.67%
Me 5	(Tanaboriboon & Guyano, 1989)	1	3.33%
Me 6	(Mozer, 1994)	7	23.33%
Me 7	(Jaskiewicz, 1999)	15	50.00%
Me 8	(HCM, 2000)	1	3.33%
Me 9	(Gallin, 2001)	11	36.67%
Me 10	(Landis et al, 2001)	12	40.00%
Me 11	(Bogota, 2005)	8	26.67%
Me 12	(Muraleetharan et al, 2005)	8	26.67%
Me 13	(Petritsch et al, 2006)	3	10.00%
Me 14	(Jensen, 2007)	1	3.33%
Me 15	(Dandan et al, 2007)	1	3.33%
Me 16	(Muraleetharan & Hagiwara, 2007)	10	33.33%
Me 17	(FDOT, 2009)	10	33.33%
Me 18	(HCM, 2010)	8	26.67%
Me 19	(Christopoulou & Pitsiava-Latinopoulou, 2012)	12	40.00%
Me 20	(Kim, Choi, & Kim, 2013)	4	13.33%
Me 21	(Kim et al, 2014)	1	3.33%
Me 22	(Talavera-Garcia & Soria-Lara, 2015)	14	46.67%
Me 23	(HCM, 2016)	11	36.67%
Me 24	(Choi et al, 2016)	0	0.00%
Me 25	(Marisamynathan & Lakshmi, 2016)	6	20.00%
Me 26	(Sahani, Ojha, & Bhuyan, 2017)	4	13.33%
Me 27	(Macdonald et al, 2018)	4	13.33%
Me 28	(Bivina et al, 2018)	11	36.67%

From the results in Table 4.4, the methodology proposed by Jaskiewicz, (1999) best represents Bogotá's local conditions with a match score of 15 out of 30. In contrast, the methodology proposed by Choi et al., (2016) had the lowest capability to evaluate Bogotá's local conditions, with a score of 0 out of 30. However, the score is not the only indicator to measure the methodologies' performances. The error variability, obtained from the differences presented between the forecasted PPSI value and the QoS perceived by the pedestrians on each sidewalk was also considered to evaluate the methodologies' performances (Figure 4.1).

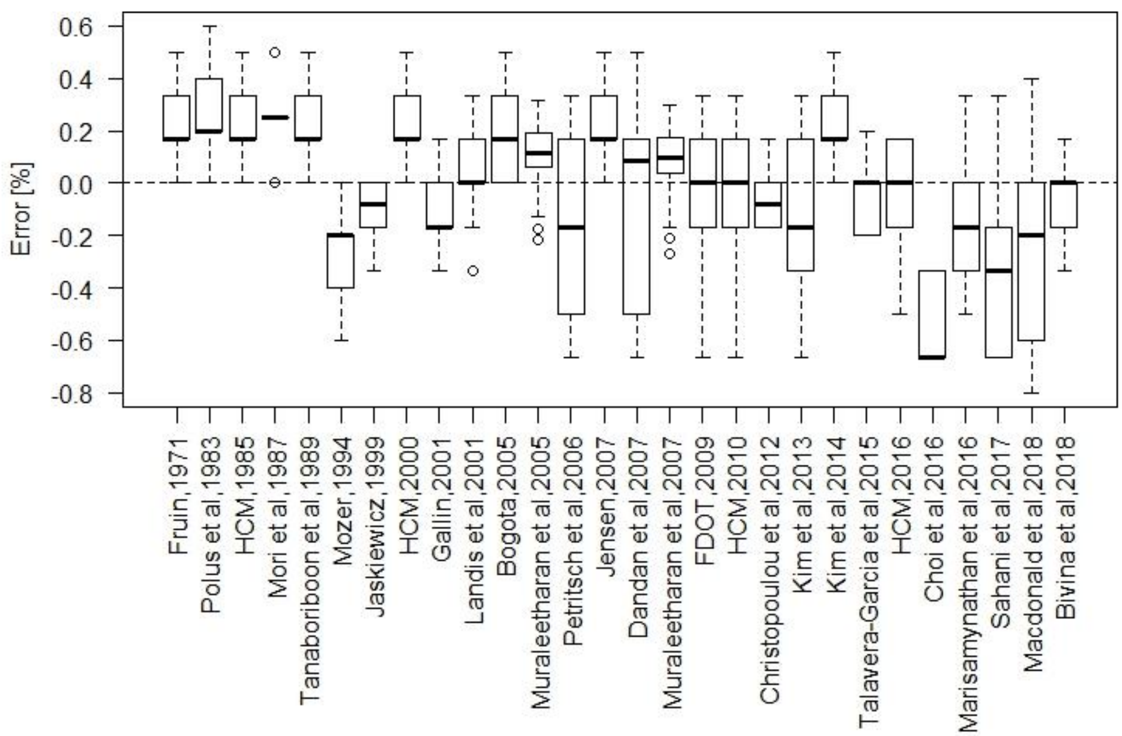

Figure 4.1. Methodologies' errors boxplot

Concerning these error measure, most methodologies proposed in the 20th century predict the PPSI to have a higher value than the QoS of the sidewalks. On the other hand, methodologies proposed after 2016 predict the PPSI more conservatively. However, the methodologies proposed between the years 2000 and 2016 perform better in terms of error variability, with variations around an error of 0%. Of these, the methods proposed by the State of Florida Department of Transportation (2009) and by the Transportation Research Board (2010, 2016), perform better in terms of error variability for Bogotá (with a median of 0% and variability around this median).

However, the previously mentioned methodologies use different inputs (flow-capacity relation, objective attributes, and expert judgement) to calculate their PPSI. For this reason, the performance results for the methodologies that consider the previously-mentioned inputs, one by one, will be presented later. Table 4.5 shows the results for different inputs in terms of mean and maximum performance rendered by the methods in each group. The mean performance was calculated by averaging the match score for the different methodologies considering each group of inputs. In addition, complete performance results for each group of inputs can be seen in Figure 4.2, Figure 4.4, and Figure 4.6.

Table 4.5. Methodologies' results per approximation

Methodologies groups	Count	Mean performance [%]	Max performance [%]
Total	28	20.60%	50.00%
Flow-capacity	8	8.75%	26.67%
Objective	14	22.14%	46.67%
Expert judgement	6	32.78%	50.00%

Most methodologies use the measurement of objective attributes to calculate their PPSI (50%). The methodologies that consider the flow-capacity relationship represent 29% of the total, and those based on expert judgement represent 21% (the least represented group, see Table 4.5).

In terms of performance mean, the methodologies based on expert judgement best represent Bogotá users' statements (see Table 4.5). This group of methodologies includes that which best represents the local conditions of Bogotá, rendering a maximum performance of 50% (see Table 4.5). On the other hand, those least capable of evaluating Bogotá's local conditions are the flow-capacity methods with a mean of 8.75% and a maximum of 26.67% for their performance (see Table 4.5). Finally, the objective-based PPSIs methodologies present a mean of 22.14% and a maximum of 46.67% for their performance (see Table 4.5).

To expand on the results obtained, the methodologies' performance and errors were divided into the previously mentioned groups. Results for the methodologies based on the flow-capacity relations are shown in Figure 4.2 and Figure 4.3. Similarly, results for the methodologies based on objective attributes are shown in Figure 4.4 and Figure 4.5. Finally, results for the methodologies based on expert judgement are shown in Figure 4.6 and Figure 4.7.

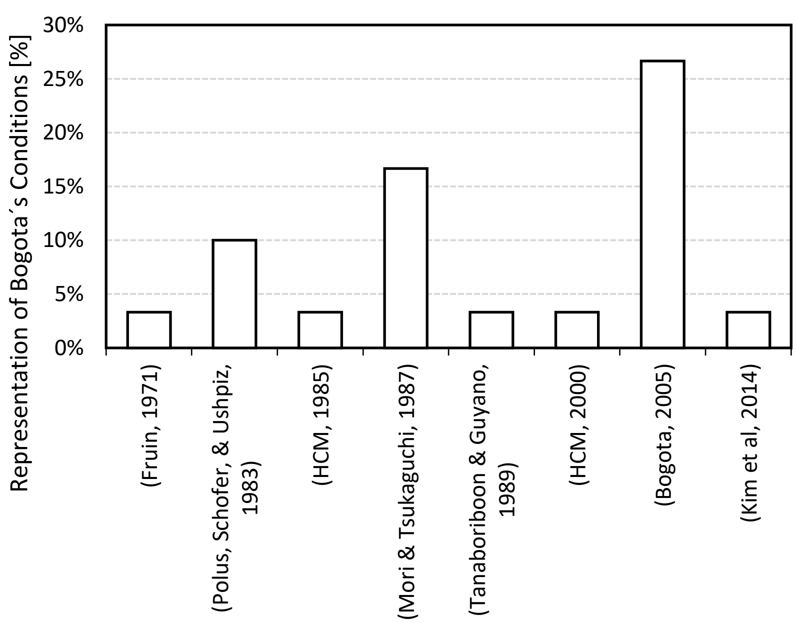

Figure 4.2. Performance of flow-capacity based methodologies

In this group, the first PPSI method proposed is that developed by Fruin (1971), with a performance below 5% (see Figure 4.2 and Table 4.4). Methodologies that consider the flow-capacity relationship were the most commonly proposed methodologies for the calculation of PPSI before the year 2000. Their performance did not improve because they evolved, but because the PPSI's possible results groups were reduced (see Appendix B – Methodological review). However, it was found that the methodology proposed by Alcaldia Mayor de Bogota D.C. (2005), which is a calibrated version for Bogotá of that proposed by the Transportation Research Board (2000), has a performance of 26.67% (see Table 4.4), which is the best one for this group of methodologies (see Figure 4.2).

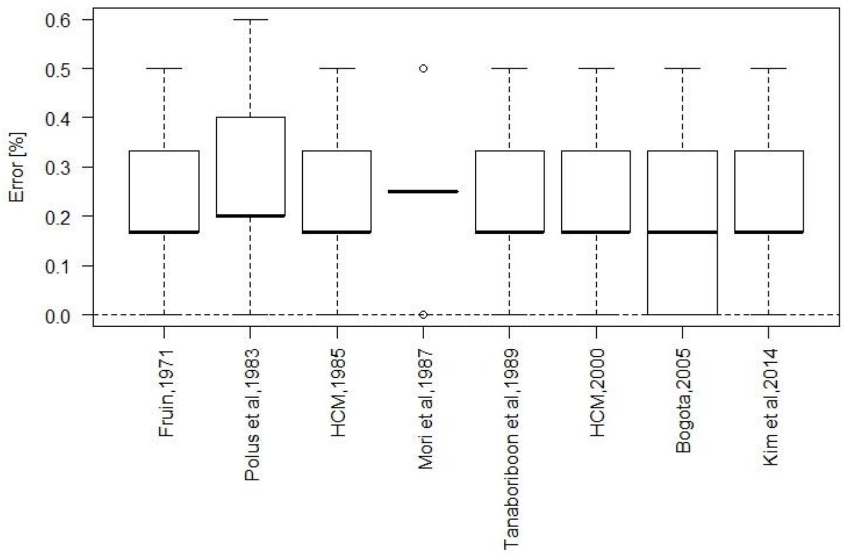

Figure 4.3. Flow-capacity relation methodologies errors boxplot

Concerning errors, the proposed methodologies using a flow-capacity relationship, predict the PPSI to be higher than the SQoS of the sidewalks. Similarly, there are no variations between the errors obtained from almost all methodologies in this category. However, there are two that are different. The methodology proposed by Mōri & Tsukaguchi (1987) does not present much variation when it is applied to different sidewalks, with a positively located interquartile range of error variability with value 0. On the other hand, the methodology proposed by Alcaldia Mayor de Bogota D.C. (2005), has the largest interquartile range in comparison with the other methods, reaching an error value of 0 for the first quartile (see Figure 4.3).

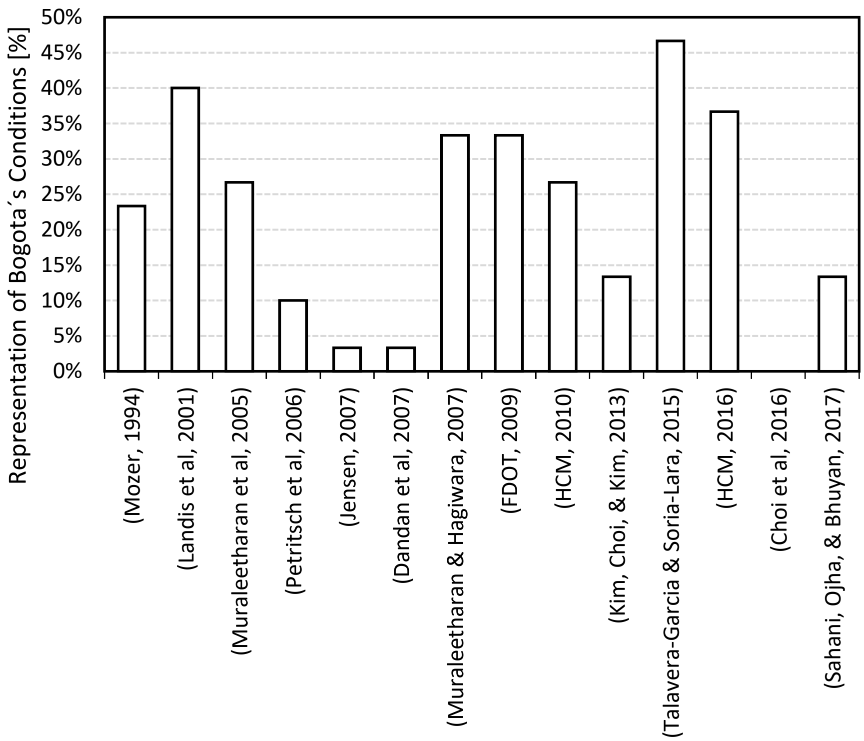

Figure 4.4. Performance of objective attributes-based methodologies

The first methodology to consider objective attributes was proposed by Mozer (1994), with a performance of 23.33% for Bogotá (see Figure 4.4 and Table 4.4). The next methodology for this group was proposed by B. Landis et al. (2001) and has a performance of 40%, representing an improvement in comparison with the previous ones (see Figure 4.4 and Table 4.4). However, this improvement was not constant and the performance of the four methodologies that followed — Dandan et al. (2007), Jensen (2007), Muraleetharan et al. (2005), and Petritsch et al. (2006) — decreased when applied to the case of Bogotá, reaching values of 3.33% (see Figure 4.4 and Table 4.4). This tendency was repeated in the case of the four following methodologies (S. Kim et al., 2013; Muraleetharan & Hagiwara, 2007; State of Florida Department of Transportation, 2009; Transportation Research Board, 2010), with an initial performance of 33.33% for Muraleetharan & Hagiwara (2007) and a decrease in performance reaching values of 13.33% (see Figure 4.4 and Table 4.4). After this last stage, another methodology was proposed by Talavera-Garcia & Soria-Lara (2015), which had a performance of 46.67%, that is, the best performance rendered by the methodologies based on objective attributes. However, subsequent methodologies did not improve in performance, but conversely, decreased in performance, reaching values of 0%. In general, the improvement of the performance for these methodologies varies over the years from 0% (Choi et al., 2016) to 46.67% (Talavera-Garcia & Soria-Lara, 2015).

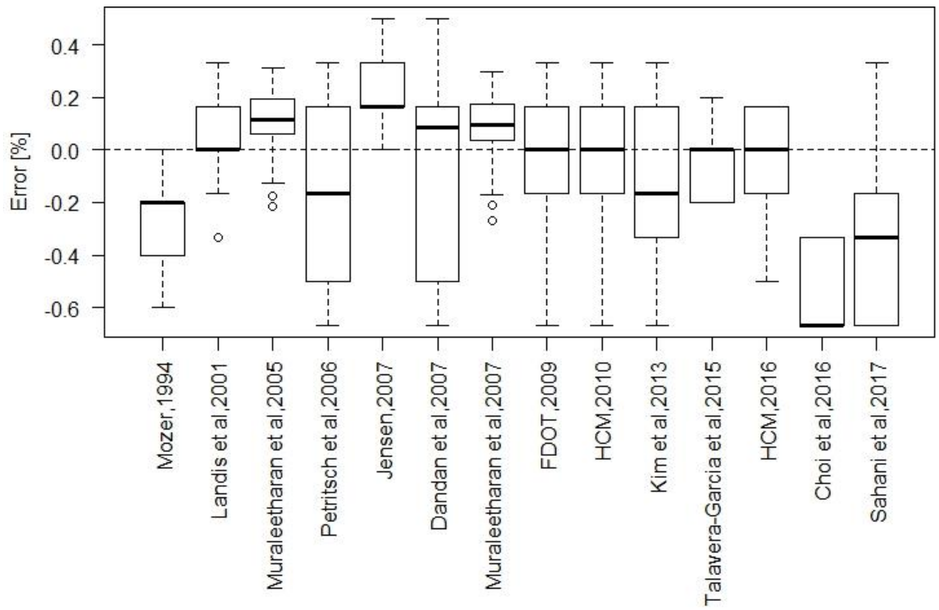

Figure 4.5. Objective attributes methodologies errors boxplot

Considering the variability of the errors, there is also an improvement in the methodologies based on objective attributes. Error variability of this group of inputs is generated around an error of 0%. However, there are some exceptions to this tendency. On the one hand, the methodology proposed by Jensen (2007) has mainly positive errors indicating a PPSI prediction higher than that which the sidewalk is rendering. On the other hand, the methodologies proposed by Choi et al. (2016) and Mozer (1994) have mainly negative errors indicating a PPSI prediction lower than that provided by the sidewalk. However, with this group of inputs there are methodologies that have errors of around 0% and a median of 0%. On one hand, the methodology proposed by B. Landis et al. (2001) has a median value of 0% with most of the error values being positive. On the other hand, the methodology proposed by Talavera-Garcia & Soria-Lara (2015) also has a median value of 0% but most of the error values are negative. In addition, the methodologies proposed by the State of Florida Department of Transportation (2009) and by the Transportation Research Board (2010, 2016) perform better in terms of error variability when applied to Bogotá, with a median of 0% and error values around the median (see Figure 4.5).

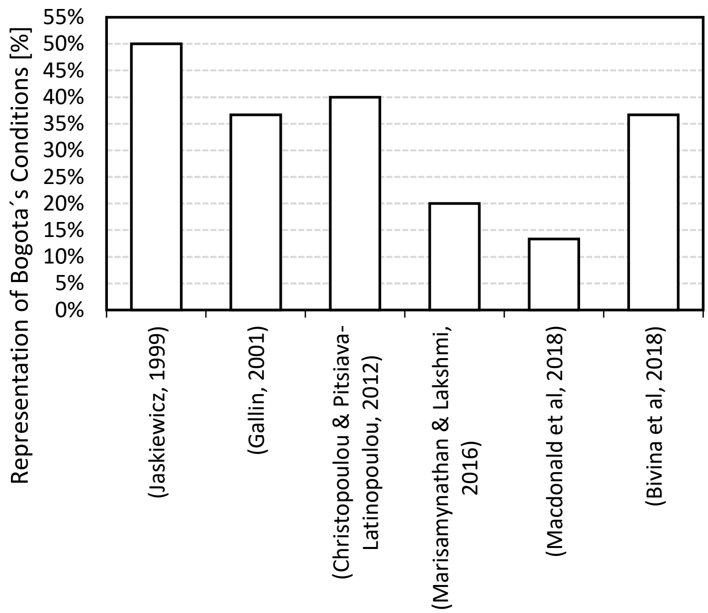

Figure 4.6. Performance of expert judgement-based methodologies

The first methodology that used expert judgements to calculate PPSI was proposed by Jaskiewicz (1999), and it had a performance of 50% for Bogotá, rendering it the best performance for all sidewalks in comparison to all other methodologies presented in this study (see Figure 4.6 and Table 4.4). The tendency to evolve and improve as seen in other methodology groups does not apply to the methods based on expert judgements, as those proposed by Bivina et al. (2018), Christopoulou & Pitsiava-Latinopoulou (2012), Gallin (2001), Macdonald et al. (2018), and Marisamynathan & Lakshmi (2016), decreased in performance, reaching a value of 13.33% (see Figure 4.6 and Table 4.4).

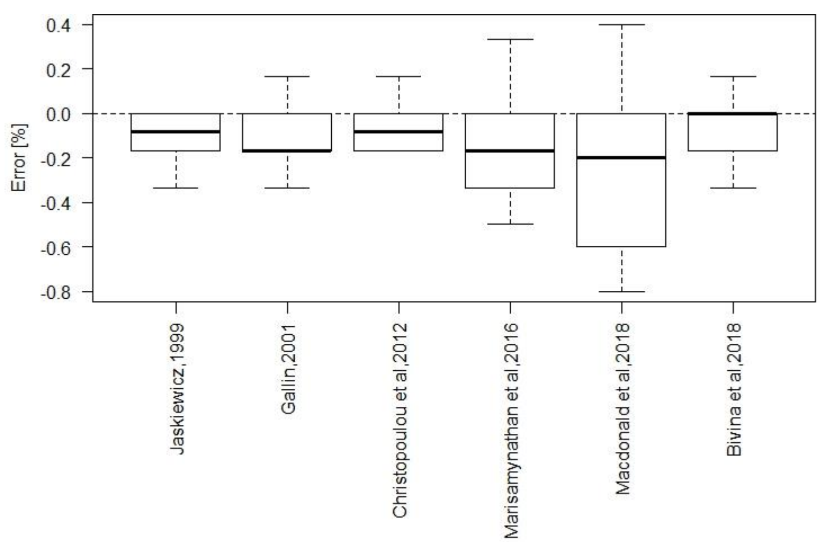

Figure 4.7. Expert judgement-based methodologies errors boxplot

Methodologies using expert judgements to predict the PPSI performed similarly in terms of errors. In this case, these methodologies predict the PPSI to have lower values in comparison to the SQoS rendered by the sidewalks. However, the methodology proposed by Bivina et al. (2018) has a median and third quartile equal to 0%, and is one of the methodologies of this group with a lower error variability. Similarly, the methodologies proposed by Christopoulou & Pitsiava-Latinopoulou (2012) and Jaskiewicz (1999) have the lowest error variability not only for the expert judgement-based methodologies, but also for all the methodologies presented in this study (see Figure 4.7).

The methodologies based on flow-capacity relation were the first, historically, proposed to calculate PPSI, but are clearly not the best in terms of performance. Those based on objective attributes have results with an error variability of around 0%, but with higher variability in comparison to the expert judgement-based methodologies. In addition, the expert judgement-based methodologies have the best mean and total performance. Similarly, the expert judgement-based methodologies have the lowest error variation, in spite of the small number of studies of this type found in the literature (see Table 4.5).

5. The influence of perceptions on the QoS

By uncovering the effects of perceptions on the perceived QoS, the previous results that found that methodologies that calculate PPSI based on expert perceptions perform better than others, can be taken advantage of. These effects will be uncovered by analyzing the individual and joint effects of different groups of attributes (environmental, sociodemographic, physical, and perceptual) on the perceived QoS. First, models will be generated by considering the groups individually as independent variables. Then, the groups in pairs and groups of threes and fours will be treated as independent variables. In addition, a cognitive map describing how pedestrians perceive the QoS from their perceptions of different sidewalk attributes will be developed.

The first step is to distinguish the overall contribution of the four different groups of attributes from the overall QoS explanation (see Table 3.10). To start, a regression analysis was done considering QoS to be the dependent variable, without combining the different groups of attributes. From this regression, the coefficient of determination (R^2) was used to quantify how much of the total variance for the dependent variable was explained by the different groups of attributes independent of each other.

We found that a model using only the environmental attributes explained the total variance of the dependent variable least ($R^2 = 0.010$). In addition, a model using sociodemographic attributes only also explains little of the total variance ($R^2 = 0.026$). Similarly, a model using only physical attributes as independent variables explains much more of the total variance in the dependent variable ($R^2 = 0.229$). Finally, a model using only perception attributes explains best the total variance of the perceived QoS ($R^2 = 0.574$, see Figure 5.1 and Table 5.1).

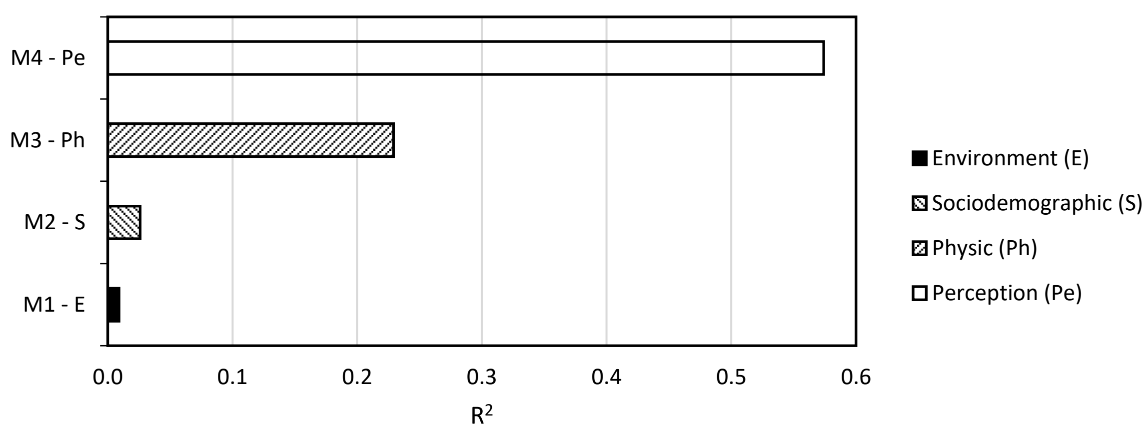

Figure 5.1. Proportion of the total variance explained by individual group regressions

Table 5.1. Individual contribution to the overall R^2

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perceptual (Pe)
M1 - E	0.009			
M2 - S		0.026		
M3 - Ph			0.229	
M4 - Pe				0.574

The same analysis was carried out again, but this time, the different attribute groups were considered as independent variables in pairs. This analysis was carried out twice for each pair, and each time the order in which a group was included in the model was changed, to quantify the upper and lower bounds of the contribution of each group of attributes. The models that contained perception attributes explained more of the total variance of the perceived QoS. On the other hand, the models containing environmental and sociodemographic attributes explained the total variance of the dependent variable least (see Figure 5.2).

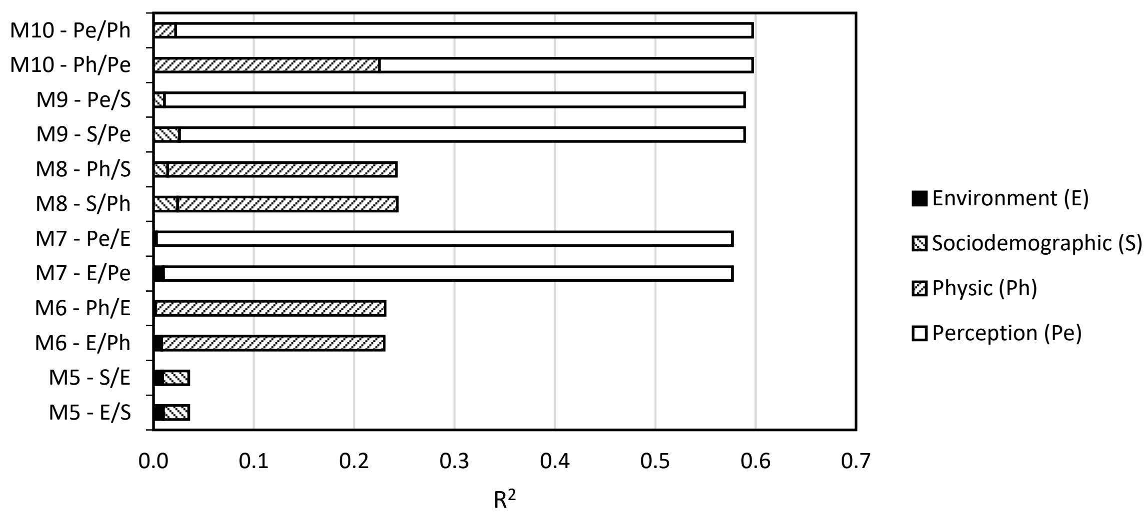

Figure 5.2. Proportion of the total variance explained by group regressions in pairs

A model using physical and perception attributes explained the total variance of the perceived QoS most ($R^2 = 0.597$). However, there is a difference in how much each group of variables contributes to the R^2 depending on the order that this group is entered into the model (see Table 5.3). When the environmental attributes are considered as an independent variable, the lowest contribution of this group to the R^2 is 0.002 and the greatest is 0.010. Considering the sociodemographic attributes as the independent variable, the lowest contribution of this group to the R^2 is 0.011 and the greatest is 0.026. The physical attributes as independent variable contribute 0.022 to the R^2 at the lowest and 0.229 at the greatest, values that overlap with the contribution of the R^2 generated by the sociodemographic attributes. Finally, the perception attributes as independent variables contribute 0.372 to the R^2 at the lowest and 0.578 at the greatest (see Table 5.2).

Table 5.2. Disaggregated contribution to the overall R^2 considering pairs of grouped attributes

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perceptual (Pe)	R^2
M5 - E/S	0.010	0.025			0.035
M5 - S/E	0.009	0.026			0.035
M6 - E/Ph	0.008		0.222		0.230
M6 - Ph/E	0.002		0.229		0.231
M7 - E/Pe	0.010			0.567	0.577
M7 - Pe/E	0.003			0.574	0.577
M8 - S/Ph		0.024	0.219		0.243
M8 - Ph/S		0.014	0.228		0.242
M9 - S/Pe		0.026		0.563	0.589
M9 - Pe/S		0.011		0.578	0.589
M10 - Ph/Pe			0.225	0.372	0.597
M10 - Pe/Ph			0.022	0.575	0.597

The same analysis can be carried out to discover how much each group of variables contributes to the total R^2. When environmental attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 1% and the greatest is 29%. The sociodemographic attributes as independent variables contribute 2% to the R^2 at the lowest and 74% at the greatest. Physical attributes as independent variables contribute 4% to the R^2 at the lowest and 99% at the greatest. Finally, the perception attributes as independent variables contribute 62% to the R^2 at the lowest and 99% at the greatest (see Table 5.3). However, these results cannot be compared because the calculated contribution is not standardized.

Table 5.3. R^2 contribution of regressions of groups by pairs

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perception (Pe)
M5 - E/S	29%	71%		
M5 - S/E	26%	74%		
M6 - E/Ph	3%		97%	
M6 - Ph/E	1%		99%	
M7 - E/Pe	2%			98%
M7 - Pe/E	1%			99%
M8 - S/Ph		10%	90%	
M8 - Ph/S		6%	94%	
M9 - S/Pe		4%		96%
M9 - Pe/S		2%		98%
M10 - Ph/Pe			38%	62%
M10 - Pe/Ph			4%	96%

The same analysis was carried out, but this time the different attribute groups considered as independent variables were included in groups of three. This analysis was carried out five times for each group of three, changing the order in which each attribute group was included into the model, to quantify the upper and lower bounds of each attribute group's contribution. The models containing perception attributes explain more of the total variance of the QoS perceived by pedestrians (see Figure 5.3).

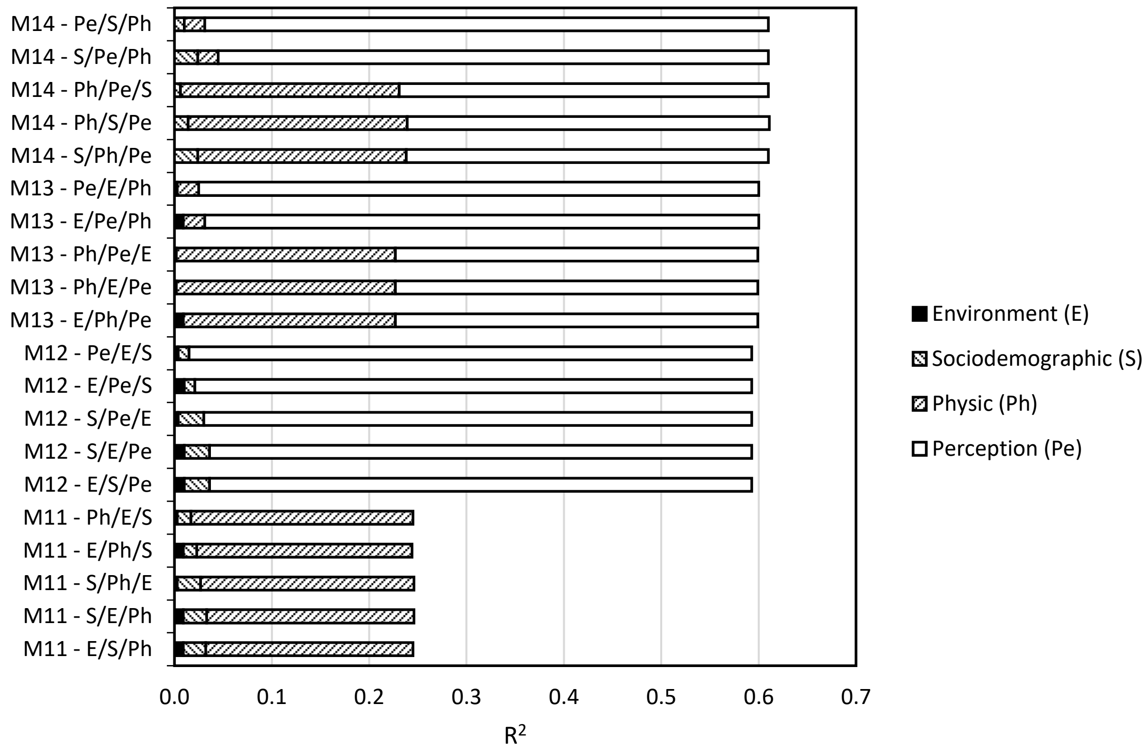

Figure 5.3. Proportion of the total variance explained by regressions of the groups of three

From these results, it can be suggested that the model that includes sociodemographic, physical, and perception attributes explains more total variance of the perceived QoS (r^2 = 0.611). However, in this case, the order of group inclusion into the model generates a minor difference in the calculation of the total R^2 (see Table 5.4). In addition, there is also a difference in the R^2 contribution of each group of variables depending on the order that the groups were entered into the model (see Table 5.5).

When the environmental attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.002 and the greatest is 0.010. The sociodemographic attributes considered as independent variables contribute 0.006 to the R^2 at the lowest and 0.026 at the greatest, values that overlap with the contribution to the R^2 generated by the environmental attributes. When the physical attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.021 and the greatest is 0.228, values that overlap with the contribution to the R^2 generated by the physical attributes. Finally, when the perception attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.372 and the greatest is 0.579 (see Table 5.4).

Table 5.4. Disaggregated contribution to the overall R^2 considering attribute groups in threes

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perception (Pe)	R^2
M11 - E/S/Ph	0.009	0.023	0.213		0.245
M11 - S/E/Ph	0.009	0.024	0.213		0.246
M11 - S/Ph/E	0.003	0.024	0.219		0.246
M11 - E/Ph/S	0.009	0.014	0.221		0.244
M11 - Ph/E/S	0.003	0.014	0.228		0.245
M12 - E/S/Pe	0.010	0.026		0.557	0.593
M12 - S/E/Pe	0.010	0.026		0.557	0.593
M12 - S/Pe/E	0.004	0.026		0.563	0.593
M12 - E/Pe/S	0.010	0.011		0.572	0.593
M12 - Pe/E/S	0.004	0.011		0.578	0.593
M13 - E/Ph/Pe	0.009		0.218	0.372	0.599
M13 - Ph/E/Pe	0.002		0.225	0.372	0.599
M13 - Ph/Pe/E	0.002		0.225	0.372	0.599
M13 - E/Pe/Ph	0.009		0.022	0.569	0.600
M13 - Pe/E/Ph	0.003		0.022	0.575	0.600
M14 - S/Ph/Pe		0.024	0.214	0.372	0.610
M14 - Ph/S/Pe		0.014	0.225	0.372	0.611
M14 - Ph/Pe/S		0.006	0.225	0.379	0.610
M14 - S/Pe/Ph		0.024	0.021	0.565	0.610
M14 - Pe/S/Ph		0.010	0.021	0.579	0.610

When the environmental attributes are considered as independent variables, the lowest contribution of this group to the R^2 is almost 0% and the greatest is 4%. In the case where the sociodemographic attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 1% and the greatest is 10%. In the case where the physical attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 3% and the greatest is 93%. Finally, in the case of the perception attributes considered as independent variables, the lowest contribution of this group to the R^2 is 61% and the greatest is 97% (see Table 5.4). In this case the results presented cannot be compared because the calculated contribution is not standardized.

Table 5.5. Contribution of group regressions in threes to the R^2

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perception (Pe)
M11 - E/S/Ph	4%	9%	87%	
M11 - S/E/Ph	4%	10%	87%	
M11 - S/Ph/E	1%	10%	89%	
M11 - E/Ph/S	4%	6%	91%	
M11 - Ph/E/S	1%	6%	93%	
M12 - E/S/Pe	2%	4%		94%
M12 - S/E/Pe	2%	4%		94%
M12 - S/Pe/E	1%	4%		95%
M12 - E/Pe/S	2%	2%		96%
M12 - Pe/E/S	1%	2%		97%
M13 - E/Ph/Pe	2%		36%	62%
M13 - Ph/E/Pe	0%		38%	62%
M13 - Ph/Pe/E	0%		38%	62%
M13 - E/Pe/Ph	2%		4%	95%
M13 - Pe/E/Ph	1%		4%	96%
M14 - S/Ph/Pe		4%	35%	61%
M14 - Ph/S/Pe		2%	37%	61%
M14 - Ph/Pe/S		1%	37%	62%
M14 - S/Pe/Ph		4%	3%	93%
M14 - Pe/S/Ph		2%	3%	95%

Finally, the same analysis was carried out and all attribute groups were considered together as independent variables. This analysis was developed ten times, each time changing the order that the groups are into the model, to quantify the upper and lower bounds of contribution of each attribute group. This time, the explanation of the total variance of the perceived QoS is similar in all the models, and only the contribution of the different attribute groups change (see Figure 5.4).

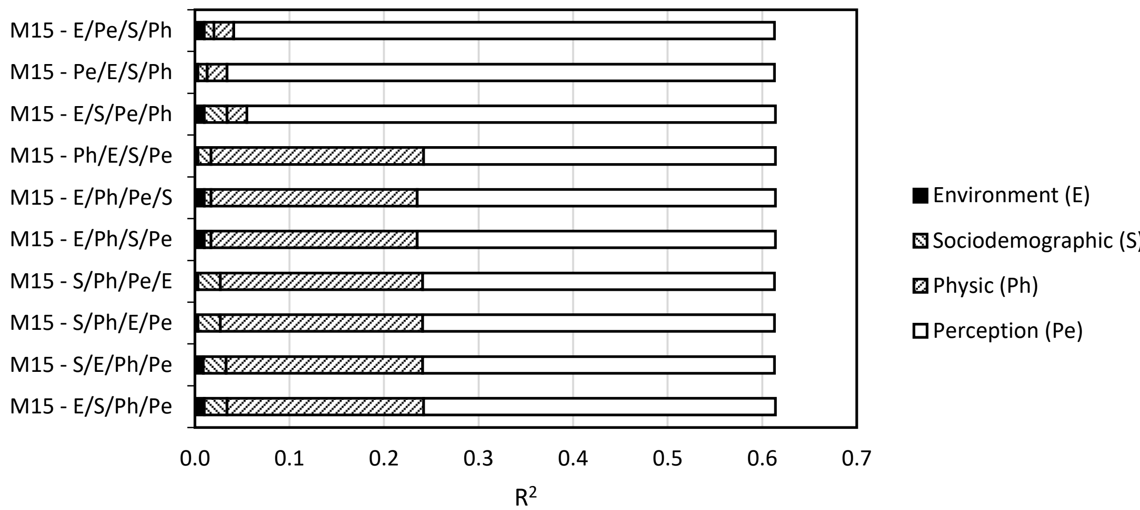

Figure 5.4. Proportion of the total variance explained by regressions of total groups

The model that explains the most total variance of the perceived QoS does not depend on the order of groups into the model, generating an R^2 of 0.614 (see Table 5.6). When the environmental attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.003 and the greatest is 0.010. Where the sociodemographic attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.007 and the greatest is 0.024, values that overlap with the contribution to the R^2 generated by the environmental attributes. Where the physical attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.021 and the greatest is 0.225, values that overlap with the contribution to the R^2 generated by the physical attributes. Finally, where the perception attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 0.372 and the greatest is 0.579, which does not overlap with any of the other figures obtained (see Table 5.6).

Table 5.6. Disaggregated contribution to the overall R^2 considering all groups of attributes

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perception (Pe)	R^2
M15 - E/S/Ph/Pe	0.010	0.024	0.208	0.372	0.614
M15 - S/E/Ph/Pe	0.009	0.024	0.208	0.372	0.613
M15 - S/Ph/E/Pe	0.003	0.024	0.214	0.372	0.613
M15 - S/Ph/Pe/E	0.003	0.024	0.214	0.372	0.613
M15 - E/Ph/S/Pe	0.010	0.007	0.218	0.379	0.614
M15 - E/Ph/Pe/S	0.010	0.007	0.218	0.379	0.614
M15 - Ph/E/S/Pe	0.003	0.014	0.225	0.372	0.614
M15 - E/S/Pe/Ph	0.010	0.024	0.021	0.559	0.614
M15 - Pe/E/S/Ph	0.003	0.010	0.021	0.579	0.613
M15 - E/Pe/S/Ph	0.010	0.010	0.021	0.572	0.613

There is also a difference in the R^2 contribution of each group of variables depending on the order in which the groups are entered into the model when considering the contribution of each group of variables to the total R^2 (see Table 5.7). When the environmental attributes are considered as independent variables, the lowest contribution of this group to the R^2 is almost 0% and the greatest is 2%. When the sociodemographic attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 1% and the greatest is 4%, values that overlap with the percentage contribution to the R^2 generated by the environmental attributes. When the physical attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 3% and the greatest is 37%, values that overlap with the percentage contribution to the R^2 generated by the physical attributes. Finally, when the perception attributes are considered as independent variables, the lowest contribution of this group to the R^2 is 61% and the greatest is 94%, which does not overlap with any of the other percentages obtained (see Table 5.7). In this case, the results can be compared because the calculated contribution for each model considers the inclusion of all groups of variables.

Table 5.7. Regressions of total groupings' contribution to R^2

Model	Environment (E)	Sociodemographic (S)	Physic (Ph)	Perception (Pe)
M15 - E/S/Ph/Pe	2%	4%	34%	61%
M15 - S/E/Ph/Pe	1%	4%	34%	61%
M15 - S/Ph/E/Pe	0%	4%	35%	61%
M15 - S/Ph/Pe/E	0%	4%	35%	61%
M15 - E/Ph/S/Pe	2%	1%	36%	62%
M15 - E/Ph/Pe/S	2%	1%	36%	62%
M15 - Ph/E/S/Pe	0%	2%	37%	61%
M15 - E/S/Pe/Ph	2%	4%	3%	91%
M15 - Pe/E/S/Ph	0%	2%	3%	94%
M15 - E/Pe/S/Ph	2%	2%	3%	93%

In addition to the analysis outlined above, the model that explains more of the total variance of the perceived QoS was identified. To do so, the adjusted R^2 and F-value of the regression were calculated (see Table 5.8).

Table 5.8. Adjusted R^2 and F-value for the models' regressions

Model	Adjusted R^2	F-value (regression)
M1	0.005	2.341
M2	0.024	2.442
M3	0.190	5.945
M4	0.564	27.138
M5	0.027	2.351
M6	0.189	5.526
M7	0.565	25.236
M8	0.198	4.595
M9	0.564	19.024
M10	0.563	13.492
M11	0.197	4.359
M12	0.565	18.063
M13	0.564	13.040
M14	0.559	10.821
M15	0.560	10.507

Two models (M7 and M12) can be selected as having the best fit using the adjusted R^2 as the goodness of fit indicator. Both models use the perception and environmental attributes as independent variables. Using the F-value of the regression as the indicator for choosing the best model, one model (M4) appears to be the best. This model was developed using the perception attributes as independent variables. There are three different options to identify which attributes, used as independent variables, generate the best model in terms of goodness of fit. Nonetheless, the three models all use the perception group as independent variables to explain the perceived QoS variance. To identify the best model considering both adjusted R^2 and F-value, a MAUT analysis was carried out by weighting each of the goodness of fit indicators. Through this analysis, a value between 0 and 1 was obtained for each model; where this value is higher it is suggested that the model is better in terms of goodness of fit. The results obtained for each model are presented in Table 5.9 and the comparison positions of different models are presented in Table 5.10.

Table 5.9. MAUT results for adjusted R^2 and F-value comparison

Model	Adjusted R^2 importance										
	0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
M1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M2	0.004	0.007	0.010	0.013	0.016	0.019	0.022	0.025	0.028	0.031	0.034
M3	0.145	0.164	0.182	0.201	0.219	0.238	0.256	0.275	0.293	0.312	0.330
M4	1.000	1.000	1.000	0.999	0.999	0.999	0.999	0.999	0.999	0.998	0.998
M5	0.000	0.004	0.008	0.012	0.016	0.020	0.024	0.028	0.032	0.035	0.039
M6	0.128	0.148	0.168	0.188	0.208	0.229	0.249	0.269	0.289	0.309	0.329
M7	0.923	0.931	0.939	0.946	0.954	0.962	0.969	0.977	0.985	0.992	1.000
M8	0.091	0.116	0.142	0.167	0.192	0.218	0.243	0.269	0.294	0.319	0.345
M9	0.673	0.705	0.738	0.770	0.803	0.835	0.868	0.901	0.933	0.966	0.998
M10	0.450	0.504	0.559	0.614	0.668	0.723	0.778	0.832	0.887	0.942	0.996
M11	0.081	0.108	0.134	0.160	0.186	0.212	0.238	0.264	0.291	0.317	0.343
M12	0.634	0.671	0.707	0.744	0.780	0.817	0.854	0.890	0.927	0.963	1.000
M13	0.431	0.488	0.545	0.601	0.658	0.715	0.772	0.828	0.885	0.942	0.998
M14	0.342	0.407	0.471	0.536	0.601	0.666	0.730	0.795	0.860	0.925	0.989
M15	0.329	0.395	0.462	0.528	0.594	0.660	0.726	0.793	0.859	0.925	0.991

Model four is preferred in the complete analysis. However, when the adjusted R^2 is weighted completely, there are two different models in first position (M7 and M12). These results are similar to those obtained in the previous analysis. In addition, when using the perception group as independent variables, better models in terms of goodness of fit are obtained. This suggestion can be evidenced in Table 5.10, where models containing perceptions are always located in the first positions.

Table 5.10. Order of MAUT results for adjusted R^2 and F-value comparison

Model	Adjusted R^2 importance										
	0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
M1	15	15	15	15	15	15	15	15	15	15	15
M2	13	13	13	13	13	14	14	14	14	14	14
M3	9	9	9	9	9	9	9	9	10	11	11
M4	1	1	1	1	1	1	1	1	1	1	3
M5	14	14	14	14	14	13	13	13	13	13	13
M6	10	10	10	10	10	10	10	10	12	12	12
M7	2	2	2	2	2	2	2	2	2	2	1
M8	11	11	11	11	11	11	11	11	9	9	9
M9	3	3	3	3	3	3	3	3	3	3	3
M10	5	5	5	5	5	5	5	5	5	5	6
M11	12	12	12	12	12	12	12	12	11	10	10
M12	4	4	4	4	4	4	4	4	4	4	1
M13	6	6	6	6	6	6	6	6	6	6	3
M14	7	7	7	7	7	7	7	7	7	8	8
M15	8	8	8	8	8	8	8	8	8	7	7

From the previous analysis it was possible to quantify the influence that perception attributes have on the perceived QoS. However, it is also important to understand how the perception of different sidewalk attributes influence the pedestrian perception of the QoS. For this reason, a pedestrian cognitive map was developed from the hypothetical model described graphically in Figure 2.1, through an exploratory factor analysis (EFA) and a structural equation modelling (SEM) approach. The first result from the EFA was proposed as the measurement model to be applied for the analysis (see Table 5.11).

Table 5.11. Proposed latent variables and indicators for the pedestrian cognitive map

Latent variables	Attributes
Sidewalk characteristics	Width, condition, furniture, trees, public transport access, and signage
Externalities	Vehicular road width, number of vehicular lanes, HGV flow, vehicular speed, and noise
Surroundings	Weather, lighting, odor, environment, cleanliness, and landscape
Discomfort	I prefer pedestrians to be far away from me, stress, the number of pedestrians do not let me walk here, and I prefer not to walk here
Bike hassles	Flow, speed, bikes coming in the opposite direction, and bikes that overtake me
Protection	Security, sidewalk safety, and road safety
Amenities	Restrooms, shops, and shade

From the results obtained from the EFA and CFA, a SEM analysis was carried out on thirty-two 0 to 10 scale questions. From this analysis the direct effects that latent variables generate on the perceived QoS were established. In the cases where direct effects were not statistically significative, the indirect effect that the latent variable could generate on the perceived QoS was also tested. The structural model presents a satisfactory adjustment and the results are presented in Table 5.13, Table 5.14, and Figure 5.5. No modifications were made post the evaluation of the model due to its good data fit (see Table 5.12).

Table 5.12. Goodness of fit indicators of the final model

Indicator	Explanation	Model result	Threshold accepted
χ^2/DF	This indicator measures the discrepancy between the sample and model covariances matrices corrected for degrees of freedom.	2.124	< 3.000
RMSEA	This indicator determines the model fit to the covariance matrix of the sample with unknown coefficients.	0.033	< 0.060
CFI	This indicator compares the proposed model χ^2 with a non-correlated model between latent variables.	0.953	> 0.950
SRMR	This indicator calculates the square root of the difference between the sample and the hypothesized model covariances matrix residuals.	0.038	< 0.080

The measurement model was proposed in Table 5.11, and it was tested by obtaining statistically significative results (see Table 5.13). From the measurement model, the existence of seven latent variables were statistically proven from thirty-one attributes of pedestrians' perceptions when walking on urban sidewalks. The most robust latent variables are the *sidewalk characteristics* and *surroundings*, with six indicators in each of these. The *externalities* contain five indicators, and the *discomfort* and *bike hassles* are composed of four indicators each. Finally, *protection* and *amenities* contain three indicators each.

Table 5.13. Standardized parameters of measurement model

Attribute	Latent variable	α	λ	t-statistic
Service quality	-	2.383	-	39.068
Width	*Sidewalk characteristics*	1.771	0.708	35.702
Condition		1.550	0.731	33.871
Furniture		1.473	0.640	28.736
Trees		1.225	0.586	24.424
Public transit access		1.650	0.422	14.636
Signage		1.363	0.625	28.392
Road width	*Externalities*	1.016	0.619	21.854
Lanes		1.034	0.621	21.677
HGV flow		1.315	0.636	21.593
Vehicular speed		1.428	0.629	21.480
Noise		2.489	0.381	11.631
Weather	*Surroundings*	2.671	0.373	12.448
Lighting		3.451	0.418	14.042
Odor		1.971	0.665	25.665
Environment		2.568	0.778	41.976
Cleanliness		1.711	0.713	35.363
Landscape		2.184	0.679	31.912
Pedestrians far from me	*Discomfort*	1.137	0.462	15.880
Stress		1.033	0.750	35.082
Too many pedestrians		1.071	0.704	31.410
I prefer not to walk here		0.942	0.631	25.918
Bike flow	*Bike hassles*	2.289	0.753	41.244
Bike speed		3.737	0.851	53.889
Opposite direction flow		2.690	0.627	27.970
Same direction flow		2.868	0.647	29.798
Security	*Protection*	1.039	0.653	28.704
Sidewalk safety		1.325	0.824	42.785
Road safety		1.401	0.726	34.565
Restrooms	*Amenities*	1.530	0.433	10.305
Shops		2.887	0.589	12.451
Shade		3.148	0.471	10.947

Additionally, the structural model was tested by obtaining statistically significative results (see Table 5.14 and Figure 5.5). From the structural model, it was statistically proven that the QoS perception is directly explained by the perception of *sidewalk characteristics* and *surroundings*. In addition, how the *sidewalk characteristics* is perceived, is affected by the perception of *surroundings*, *externalities*, *discomfort,* and *protection*. Similarly, the perception of *surroundings* is affected by how pedestrians perceive *externalities*, *discomfort*, and *protection*. In turn, the perception of *externalities* affects the way pedestrians perceive *discomfort* and *protection*. Similarly, the perception of *discomfort* affects *protection*. Finally, the way pedestrians perceive *bike hassles* and *amenities* affect the perception of *externalities* and *protection*. Indeed, the cognitive map in Figure 5 shows a complex web of interactions among variables.

Table 5.14. SEM infrastructure QoS final model results

MODEL	β and λ						
	Sidewalk characteristics	***Surrounding***	***Externalities***	***Discomfort***	***Protection***	***Bike hassles***	***Amenities***
Direct							
Service quality	0.689	0.149					
(t-statistic)	(29.040)	(5.114)					
Sidewalk characteristics		0.176	-0.363	-0.088	0.185		
(t-statistic)		(4.229)	(-7.621)	(-1.952)	(4.838)		
Surrounding			-0.196	-0.170	0.350		
(t-statistic)			(-3.940)	(-3.690)	(9.973)		
Externalities						0.156	-0.304
(t-statistic)						(3.890)	(-6.068)
Discomfort			0.527				
(t-statistic)			(14.590)				
Protection			-0.186	-0.100		-0.117	0.088
(t-statistic)			(-3.217)	(-1.972)		(-3.088)	(1.707)
Indirect							
Service quality		0.121	-0.412	-0.128	0.222	-0.091	0.145
(t-statistic)		(4.153)	(-14.736)	(-3.659)	(8.375)	(-4.839)	(6.021)
Sidewalk characteristics			-0.155	-0.055	0.062	-0.110	0.179
(t-statistic)			(-5.696)	(-3.237)	(3.868)	(-4.784)	(6.067)
Surrounding			-0.173	-0.035		-0.099	0.143
(t-statistic)			(-5.776)	(-1.933)		(-4.912)	(5.433)
Externalities							
(t-statistic)							
Discomfort						0.083	-0.160
(t-statistic)						(3.747)	(-5.561)
Protection			-0.053			-0.037	0.072
(t-statistic)			(-1.972)			(-3.126)	(3.992)
Total							
Service quality	0.689	0.270	-0.412	-0.128	0.222	-0.091	0.145
(t-statistic)	(29.040)	(7.747)	(-14.736)	(-3.659)	(8.375)	(-4.839)	(6.021)
Sidewalk characteristics		0.176	-0.519	-0.142	0.247	-0.110	0.179
(t-statistic)		(4.229)	(-15.009)	(-3.035)	(7.009)	(-4.784)	(6.067)
Surrounding			-0.369	-0.205	0.350	-0.099	0.143
(t-statistic)			(-9.482)	(-4.256)	(9.973)	(-4.912)	(5.433)
Externalities						0.156	-0.304
(t-statistic)						(3.890)	(-6.068)
Discomfort			0.527			0.083	-0.160
(t-statistic)			(14.590)			(3.747)	(5.561)
Protection			-0.238	-0.100		-0.155	0.161
(t-statistic)			(-5.224)	(-1.972)		(-4.119)	(3.348)

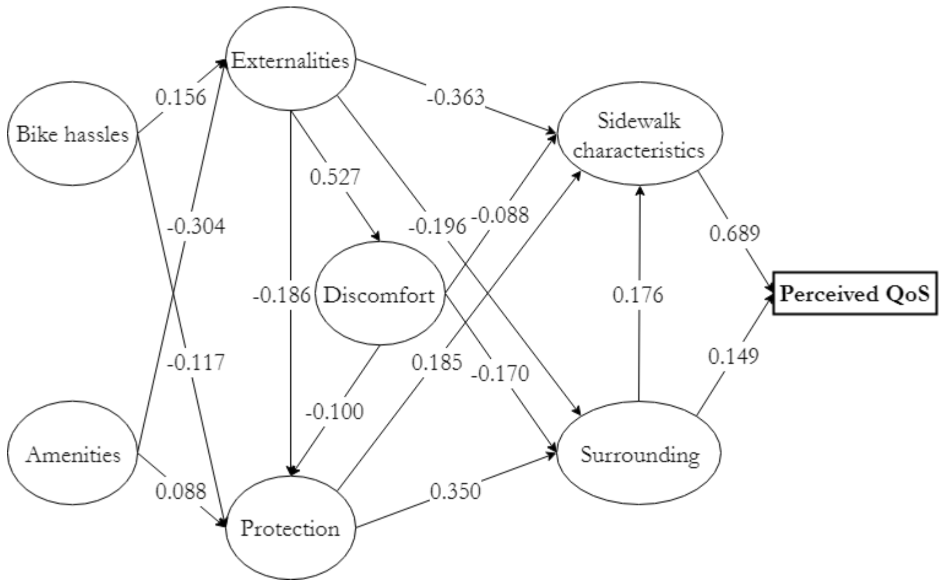

Figure 5.5. SEM infrastructure QoS final model

Perceived QoS is directly affected by two latent variables: *sidewalk characteristics* and *surroundings*; and indirectly affected by six latent variables: *surrounding*, *externalities*, *discomfort*, *protection*, *bike hassles*, and *amenities*. In the case of direct effects, the perception of QoS is directly and positively affected by the perception of *sidewalk characteristics* ($\lambda = 0.689$). Similarly, the perception of *surroundings* is directly and positively related to the perceived QoS ($\lambda = 0.149$). Additionally, when indirect effects are considered, the perception of QoS is also positively affected by the perception of the *surroundings* using the *sidewalk characteristics* as a mediator ($w = 0.121$). Similarly, the perceived QoS is also affected in a positive and indirect way by how pedestrians perceive their *protection* ($w = 0.222$) and *amenities* ($w = 0.145$), using as final mediators the perception of *surroundings* and *sidewalk characteristics*. On the other hand, the perception of *externalities* also indirectly affects the QoS perception, but in a negative way, with the final mediation of the perception of *surroundings* and *sidewalk characteristics* ($w = -0.412$). Similarly, the perceived QoS is also affected in a negative and indirect way by how pedestrians perceive *discomfort* ($w = -0.128$) and *bike hassles* ($w = -0.091$), using as final mediators the perceptions of *surroundings* and *sidewalk characteristics*.

6. Application of pedestrian perceptions for QoS forecasting

We considered the ordered probit model to be the best approach for forecasting the SQoS, because it produced the best performance indicators when validated. However, applying this model requires both objective (sidewalk and users attributes) and subjective (pedestrian perceptions) information. On the other hand, of the models that only need user and sidewalk objective attributes to explain the subjective attributes and to forecast SQoS, the ordered probit MIMIC model would be the first choice. In both cases, the proposed forecasting models represent Bogotá's local context well in comparison with the previously analyzed methodologies (see Figure 6.1). The forecasting models were based on the complete description of the effects and roles that perceptions have on and in the pedestrian QoS explanation.

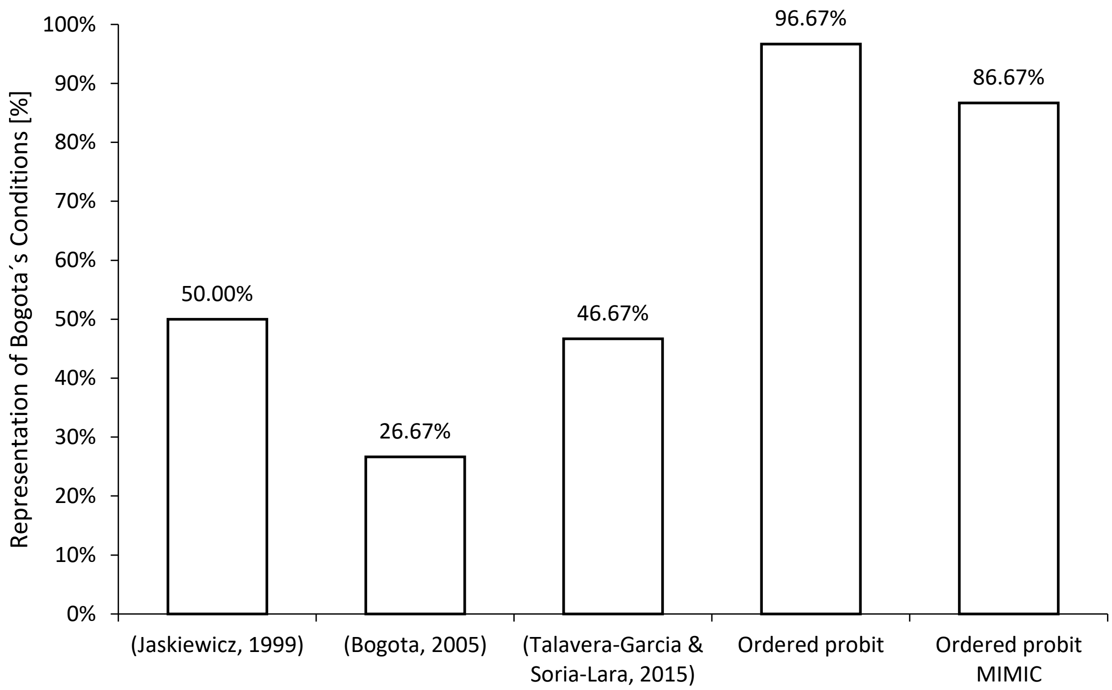

Figure 6.1. Performance of proposed forecasting models vs existing methodologies

Initially, a linear model was proposed between the pedestrian perception of QoS and the independent variables. This analysis was done using a forward approach and the final model selection was based on the lower AIC estimator value. The obtained linear model is presented in Table 6.1.

Table 6.1. Forecasting QoS linear model

Infrastructure service (QoS) forecasting by linear model					
Adjusted R^2	0.569				
F-statistic	54.590				
	Estimate	**Std. Error**	**t statistic**	**p-value**	**Sig**
(Intercept)	0.896	0.381	2.353	0.019	*
Sidewalk surface condition[1]	0.216	0.032	6.830	0.000	***
Building articulation[1]	0.243	0.031	7.918	0.000	***
Sidewalk width[1]	0.156	0.030	5.189	0.000	***
Horizontal marking[1]	0.091	0.026	3.533	0.000	***
Road safety[1]	0.050	0.023	2.182	0.030	*
Sidewalk furniture[1]	0.067	0.029	2.292	0.022	*
Heavy vehicles[1]	-0.043	0.021	-2.077	0.038	*
Lighting[1]	0.073	0.032	2.284	0.023	*
Organized space[1]	0.050	0.024	2.116	0.035	*
Tree presence[1]	0.046	0.027	1.743	0.082	.
Facade distance [m]	-0.019	0.007	-2.793	0.005	**
Trees [#]	0.019	0.012	1.597	0.111	
Age [years]	0.011	0.005	2.227	0.026	*
Vehicular flow is close to me[1]	-0.035	0.021	-1.678	0.094	.
Bike infrastructure width [m]	-0.130	0.081	-1.604	0.109	

Significance codes: *** $p < 0.001$, ** $p < 0.010$, * $p < 0.050$, · $p < 0.100$
1. Pedestrian perception responses in situ from 0 to 10

The QoS forecasting linear model presents an adjusted R^2 of 0.569 and has 15 independent variables. There are 11 perceptual variables and four objective variables. Out of the perceptual variables, nine improve the QoS perceived by pedestrians, where the perceived articulation of the different building facades and the perceived condition of the sidewalk surface are the variables that most improve the perceived QoS. On the other hand, the perceived heavy goods vehicle (HGV) flow and the perceived distance from the vehicular flow are variables that decrease the pedestrian perception of the QoS. From the objective variables, the analysis identified that the older the respondent and higher the number of trees on the sidewalk, the higher was the perceived QoS. On the other hand, the model also implied that the greater the distance from the sidewalk to the facade and the bicycle infrastructure width, the lower the perceived QoS (see Table 6.1).

An ordered probit model was also proposed when a non-linear relationship between the perceived QoS and the independent variables was considered. This analysis was carried out using a forward approach and the final model selection was based on the lower AIC estimator value. The obtained linear model is presented in Table 6.2.

Table 6.2. Forecasting QoS ordered probit model

Infrastructure service (QoS) forecasting by ordered probit model					
Nagelkerke pseudo R^2			0.588		
McFadden pseudo Rho squared			0.198		
	Estimate	**Std. Error**	**Wald statistic**	**p-value**	**Sig**
Threshold 0	-0.575	0.497	-1.156	0.248	
Threshold 1	-0.412	0.494	-0.833	0.405	
Threshold 2	0.083	0.489	0.169	0.866	
Threshold 3	0.791	0.485	1.630	0.103	
Threshold 4	1.178	0.485	2.431	0.015	*
Threshold 5	1.903	0.487	3.910	0.000	***
Threshold 6	2.363	0.490	4.824	0.000	***
Threshold 7	2.760	0.493	5.602	0.000	***
Threshold 8	3.493	0.497	7.026	0.000	***
Threshold 9	3.833	0.499	7.679	0.000	***
Sidewalk surface condition[1]	0.125	0.019	6.532	0.000	***
Building articulation[1]	0.144	0.019	7.615	0.000	***
Sidewalk width[1]	0.091	0.018	5.001	0.000	***
Horizontal marking[1]	0.053	0.015	3.390	0.001	**
Road safety[1]	0.032	0.014	2.297	0.022	*
Sidewalk furniture[1]	0.049	0.017	2.791	0.005	**
Heavy vehicles[1]	-0.034	0.012	-2.814	0.005	**
Lighting[1]	0.044	0.019	2.296	0.022	*
Organized space[1]	0.027	0.014	1.883	0.060	.
Age [years]	0.007	0.003	2.389	0.017	*
Bus stop presence (yes=1/no=0)	0.303	0.114	2.664	0.008	**
Driveway length [m]	-0.009	0.004	-2.422	0.015	*
Noise [dB]	-0.017	0.007	-2.490	0.013	*
Restroom presence (yes=1/no=0)	0.245	0.099	2.476	0.013	*
Tree presence[1]	0.030	0.014	2.047	0.041	*
Vehicular flow is close to me[1]	-0.019	0.013	-1.476	0.140	

Significance codes: *** $p < 0.001$, ** $p < 0.010$, * $p < 0.050$, · $p < 0.100$
1. Pedestrian perception responses in situ from 0 to 10

The QoS forecasting ordered probit model is made up of 16 independent variables. There are 11 perceptual variables and five objective variables. From the perceptual variables, there are nine that improve the QoS perceived by pedestrians; of these, the perceived articulation of the different building facades and the perceived condition of the sidewalk surface are those that improve the perceived QoS more. On the other hand, the perceived HGV flow and the perceived distance from the vehicular flow decreases the perceived QoS (similar to the linear model results). Looking at the objective variables, the greater the respondent's age, the higher the perceived QoS. In addition, the presence of bus stops and restrooms also increases the QoS perceived by pedestrians. On the other hand, the analysis also identified that the greater the length of driveways and the higher the noise level, the lower the perceived QoS (see Table 6.2).

In a third stage, a continuous MIMIC model was proposed to handle the case when the perception attributes could be considered as indicators explained by four different latent variables (*sidewalk characteristics*, *surroundings*, *discomfort*, and *externalities*). In this scenario, the perceived QoS is predicted using both the inferred latent variables and objective indicators which were introduced using a forward approach (see Table 6.3).

Table 6.3. Forecasting QoS continuous MIMIC model

Infrastructure service (QoS) forecasting by continuous MIMIC					
χ^2/DF[3]		1.960			
CFI[3]		0.951			
RMSEA[3]		0.036			
SRMR[3]		0.035			
Infrastructure service[1]	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
(Intercept)	5.506	0.706	7.798	0.000	***
Sidewalk characteristics[2]	0.852	0.062	13.806	0.000	**
Surroundings[2]	0.340	0.061	5.540	0.000	***
Noise [dB]	-0.022	0.010	-2.200	0.028	*
***Sidewalk characteristics*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Surroundings[2]	0.273	0.061	4.505	0.000	***
Externalities[2]	-0.144	0.031	-4.685	0.000	***
Discomfort[2]	-0.198	0.071	-2.775	0.006	**
Age [years]	0.017	0.004	3.932	0.000	***
Potholes? (yes=1/no=0)	-0.847	0.164	-5.162	0.000	***
Sidewalk width [m]	0.739	0.081	9.073	0.000	***
***Surroundings*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Externalities[2]	-0.156	0.031	-4.958	0.000	***
Discomfort[2]	-0.271	0.074	-3.670	0.000	***
Age [years]	0.013	0.004	2.960	0.003	**
Bike infrastructure width [m]	-0.244	0.109	-2.238	0.025	*
Driveway length [m]	-0.033	0.006	-5.330	0.000	***
Bikes? (yes=1/no=0)	-0.580	0.177	-3.277	0.001	**
Pedestrian flow [5 min]	-0.006	0.002	-3.770	0.000	***
Buffer width [m]	0.343	0.083	4.151	0.000	***
***Discomfort*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Externalities[2]	0.189	0.030	6.253	0.000	***
Pedestrian density [ped/m2]	4.164	0.950	4.385	0.000	***
Sidewalk width [m]	-0.144	0.058	-2.480	0.013	*
Buffer width [m]	-0.116	0.050	-2.329	0.020	*
***Externalities*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Median strip presence (yes=1/no=0)	-0.585	0.257	-2.280	0.023	*
Buffer width [m]	-0.191	0.095	-2.013	0.044	*

Significance codes: *** p < 0.001, ** p < 0.010, * p < 0.050, · p < 0.100
1. Pedestrian perception responses in situ from 0 to 10
2. Inferred latent variable
3. Explanation of each goodness of fit indicator can be found on Table 5.12

The QoS forecasting continuous MIMIC model presents a satisfactory adjustment ($\chi^2/DF = 1.960$; CFI = 0.951; RMSEA = 0.036; SRMR = 0.035) and is made up of 15 independent variables and 14 indicators of the latent variables. The independent variables consist of four latent variables and 11 objective attributes. The perceived QoS is positively influenced by two latent variables (*sidewalk characteristics* and *surroundings*) and is negatively affected by noise. The *sidewalk characteristics* is improved by the effect that *surroundings* generates on it, by the age of the pedestrians using the sidewalk, and by increasing the sidewalk width. On the other hand, the *sidewalk characteristics* value decreases with the presence of potholes in the sidewalk and with the effect of two latent variables (*externalities* and *discomfort*). The *surroundings* improves with increasing the buffer width and with the age of the pedestrians using the sidewalk. On the other hand, the *surroundings* decreases when both the bicycle infrastructure width, driveway length, bicycle presence, and pedestrian flow, increase and also with the effect of two latent variables (*externalities* and *discomfort)*. The *discomfort* is one of the latent variables that decreases the perceived QoS and its effects can be mitigated by increasing the sidewalk and buffer width. However, the effects of the *discomfort* on the perceived QoS can be aggravated by an increase in the pedestrian density and by the effect of the *externalities*. Lastly, *externalities* also decreases the perceived QoS and its effects can be mitigated by increasing the buffer width and the median strip presence (see Table 6.3).

Finally, an ordered probit MIMIC model is proposed where the perception attributes are considered as ordinal indicators explained by the existence of the same four latent variables (*sidewalk characteristics*, *surroundings*, *discomfort*, and *externalities*). In this case, the perceived QoS was estimated considering an ordinal scale, through the inferred latent variables and objective indicators using a forward approach (see Table 6.4).

Table 6.4. Forecasting QoS ordered probit MIMIC model

Infrastructure service (QoS) forecasting by ordered probit MIMIC					
χ^2/DF^3			1.737		
CFI[3]			0.989		
RMSEA[3]			0.032		
SRMR[3]			0.038		
Infrastructure service[1]	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Threshold 0	-1.039	0.184	-5.637	0.000	***
Threshold 1	-0.960	0.180	-5.330	0.000	***
Threshold 2	-0.611	0.174	-3.521	0.000	***
Threshold 3	-0.189	0.171	-1.108	0.268	
Threshold 4	0.093	0.170	0.550	0.582	
Threshold 5	0.556	0.170	3.275	0.001	**
Threshold 6	0.853	0.171	4.980	0.000	***
Threshold 7	1.116	0.171	6.508	0.000	***
Threshold 8	1.620	0.173	9.354	0.000	***
Threshold 9	1.867	0.173	10.787	0.000	***
Sidewalk characteristics[2]	1.569	0.125	12.527	0.000	***
Surroundings[2]	0.222	0.047	4.768	0.000	***
Bikes? (yes=1/no=0)	-0.250	0.096	-2.601	0.009	**
***Sidewalk characteristics*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Surroundings[2]	0.176	0.030	5.883	0.000	***
Externalities[2]	-0.125	0.026	-4.858	0.000	***
Discomfort[2]	-0.131	0.046	-2.875	0.004	**
Age [years]	0.005	0.001	3.699	0.000	***
Potholes? (yes=1/no=0)	-0.201	0.048	-4.208	0.000	***
Sidewalk width [m]	0.152	0.026	5.908	0.000	***
***Surrounding*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Externalities[2]	-0.194	0.038	-5.145	0.000	***
Discomfort[2]	-0.392	0.074	-5.331	0.000	***
Driveway length [m]	-0.010	0.003	-3.540	0.000	***
Buffer width [m]	0.112	0.025	4.445	0.000	***
***Discomfort*[2]**	**Estimate**	**Std. Error**	**t statistic**	**p-value**	**Sig**
Externalities[2]	0.277	0.030	9.129	0.000	***
***Externalities*[2]**					
Bikes? (yes=1/no=0)	0.284	0.102	2.788	0.005	**
Median strip presence (yes=1/no=0)	-0.373	0.103	-3.627	0.000	***
Buffer width [m]	-0.099	0.030	-3.261	0.001	**

Significance codes: *** p < 0.001, ** p < 0.010, * p < 0.050, · p < 0.100
1. Pedestrian perception responses in situ from 0 to 10
2. Inferred latent variable
3. Explanation of each goodness of fit indicator can be found on Table 5.12

The QoS ordered probit MIMIC model presents a satisfactory adjustment ($\chi^2/DF = 1.737$; CFI = 0.989; RMSEA = 0.032; SRMR = 0.038) and is made up of 11 independent variables and 14 indicators of the latent variables. From the independent variables there are four latent variables and seven objective attributes. The perceived QoS is positively influenced by two latent variables (*sidewalk characteristics* and *surroundings*) and is negatively affected by the presence of bicycles. The *sidewalk characteristics* is improved by the effect of the *surrounding*, by the age of the pedestrians using the sidewalk, and by increasing the sidewalk width. On the other hand, the *sidewalk characteristics* value decreases with the presence of potholes in the sidewalk and with the effect of two latent variables (*externalities* and *discomfort*). The *surroundings* is improved only by increasing the buffer width. On the other hand, the *surroundings* decreases by increasing driveway length and by the effect of two latent variables (*externalities* and *discomfort*). *Discomfort* is one of the latent variables that decreases the perceived QoS and its effects are aggravated by the influence of the *externalities*. Finally, *externalities* decreases the perceived QoS and its effects can be mitigated by increasing the buffer width and by the presence of a median strip. However, its effects can be aggravated by the presence of bicycles on the sidewalk (see Table 6.4).

Two different approaches were followed to develop the forecasting process for each sidewalk. The first was to calculate the perceived SQoS for each sidewalk by predicting the QoS for different users of each sidewalk. Once this was done, the mean of these values was calculated and was defined as the SQoS. The second approach was to calculate the perceived SQoS using the mean of the different independent variables of each sidewalk.

For the first approach, the perceived QoS for each pedestrian from a group of pedestrians using each one of the sidewalks was calculated first. This calculation was done by applying the four previously described models and was defined as QoS_{ij} for each pedestrian *i* using sidewalk *j*. Then, from the QoS_{ij}, and using Equation (16), the mean of the different pedestrians' predictions for each sidewalk was calculated to obtain the SQoS ($SQoS_{mp_j}$).

$$SQoS_{mp_j} = \frac{\sum_{i=1}^{n} QoS_{ij}}{n} \tag{16}$$

The results obtained from the first approach using the four different models described previously can be found in Table 6.5.

Table 6.5. Forecasting for sidewalk QoS using the pedestrian mean approach

Sidewalk	QoS	QoS min	QoS max	OLS_m	$Probit_m$	C. $MIMIC_m$	P. $MIMIC_m$
1	7.18	5.76	8.60	7.02	7.60	6.03	6.27
2	6.45	4.78	8.13	6.33	6.45	7.32	8.45
3	8.00	6.43	9.57	7.39	7.67	6.45	7.89
4	7.00	5.65	8.35	7.15	7.40	7.77	10.00
5	5.36	4.33	6.40	5.78	6.55	4.84	5.00
6	5.91	3.84	7.98	6.13	5.91	5.54	5.00
7	7.27	5.82	8.72	6.74	7.00	7.52	9.82
8	8.00	7.08	8.92	8.30	9.30	6.09	6.00
9	7.70	6.39	9.01	7.20	7.80	6.60	7.40
10	3.55	1.79	5.31	4.14	3.70	4.35	5.00
11	7.18	5.92	8.44	6.80	6.64	6.41	8.45
12	7.36	6.17	8.55	7.09	8.18	8.93	10.00
13	8.09	6.76	9.42	7.55	7.91	6.74	10.00
14	8.27	6.73	9.82	7.81	8.36	7.55	10.00
15	5.09	3.39	6.79	5.27	5.18	5.61	5.00
16	6.40	5.09	7.71	6.28	6.70	7.06	10.00
17	5.82	4.03	7.61	4.79	4.45	6.18	6.64
18	5.50	4.48	6.52	5.61	6.22	6.09	6.20
19	5.50	3.72	7.28	6.37	6.70	6.93	8.50
20	4.73	3.46	6.00	5.22	4.82	4.30	5.00
21	6.36	4.98	7.74	5.26	5.00	6.32	7.00
22	8.55	7.62	9.47	8.06	9.10	7.29	10.00
23	6.90	5.52	8.28	6.94	7.20	5.65	5.30
24	7.27	6.68	7.87	7.16	7.27	7.22	10.00
25	7.20	5.97	8.43	6.86	7.00	6.76	9.00
26	5.50	3.74	7.26	4.86	4.50	5.69	5.00
27	6.70	4.72	8.68	5.96	5.90	5.82	6.50
28	3.73	2.85	4.61	4.88	4.91	4.74	5.00
29	8.80	7.44	10.16	8.65	9.10	8.65	10.00
30	5.45	3.95	6.96	4.53	4.82	5.78	5.00

For the second approach, the perceived SQoS was calculated directly from the data obtained on each sidewalk according to the different independent variables needed in each of the previously described four models. This approach was defined as the SQoS for each *j* sidewalk ($SQoS_j$). The results obtained from the second approach using the four different models described previously can be found in the Table 6.6.

Table 6.6. Forecasting for sidewalk QoS using the sidewalk data

Sidewalk	QoS	QoS min	QoS max	OLS	Probit	C. MIMIC	P. MIMIC
1	7.18	5.76	8.60	7.03	7.03	6.03	5.93
2	6.45	4.78	8.13	6.33	6.61	7.32	6.61
3	8.00	6.43	9.57	7.35	7.40	6.45	6.47
4	7.00	5.65	8.35	7.32	7.62	7.77	8.15
5	5.36	4.33	6.40	5.78	6.11	4.84	5.35
6	5.91	3.84	7.98	6.13	5.83	5.54	5.36
7	7.27	5.82	8.72	6.74	6.88	7.52	7.52
8	8.00	7.08	8.92	8.30	8.81	6.09	5.85
9	7.70	6.39	9.01	7.20	7.40	6.60	6.34
10	3.55	1.79	5.31	4.03	3.90	4.36	4.46
11	7.18	5.92	8.44	6.80	6.77	6.41	6.56
12	7.36	6.17	8.55	7.09	7.68	8.93	8.33
13	8.09	6.76	9.42	7.55	7.86	6.74	6.98
14	8.27	6.73	9.82	7.81	8.15	7.55	7.59
15	5.09	3.39	6.79	5.27	5.23	5.61	5.16
16	6.40	5.09	7.71	6.28	6.47	7.06	6.99
17	5.82	4.03	7.61	4.79	4.85	6.18	6.15
18	5.50	4.48	6.52	5.54	6.22	6.09	5.99
19	5.50	3.72	7.28	6.37	6.09	6.93	6.75
20	4.73	3.46	6.00	5.22	5.03	4.30	4.46
21	6.36	4.98	7.74	5.26	5.01	6.32	6.14
22	8.55	7.62	9.47	7.93	8.42	7.29	7.54
23	6.90	5.52	8.28	6.94	6.97	5.65	5.75
24	7.27	6.68	7.87	7.16	7.14	7.22	7.07
25	7.20	5.97	8.43	6.86	6.71	6.76	6.82
26	5.50	3.74	7.26	5.21	5.24	5.70	5.45
27	6.70	4.72	8.68	5.96	5.60	5.82	5.99
28	3.73	2.85	4.61	4.88	4.95	4.74	4.68
29	8.80	7.44	10.16	8.65	8.99	8.65	8.16
30	5.45	3.95	6.96	4.53	4.81	5.78	5.64

Once the two different approaches were computed, a 95% confidence interval of the SQoS was calculated from the pedestrian survey answers to compare with the forecasting approaches (see Table 6.5 and Table 6.6). For the cases where the forecasting values were within the calculated confidence interval for each sidewalk, a score of 1 was assigned. Otherwise, a score of 0 was assigned. All the sidewalks were predicted and rated using this procedure and the results are presented in Figure 6.2.

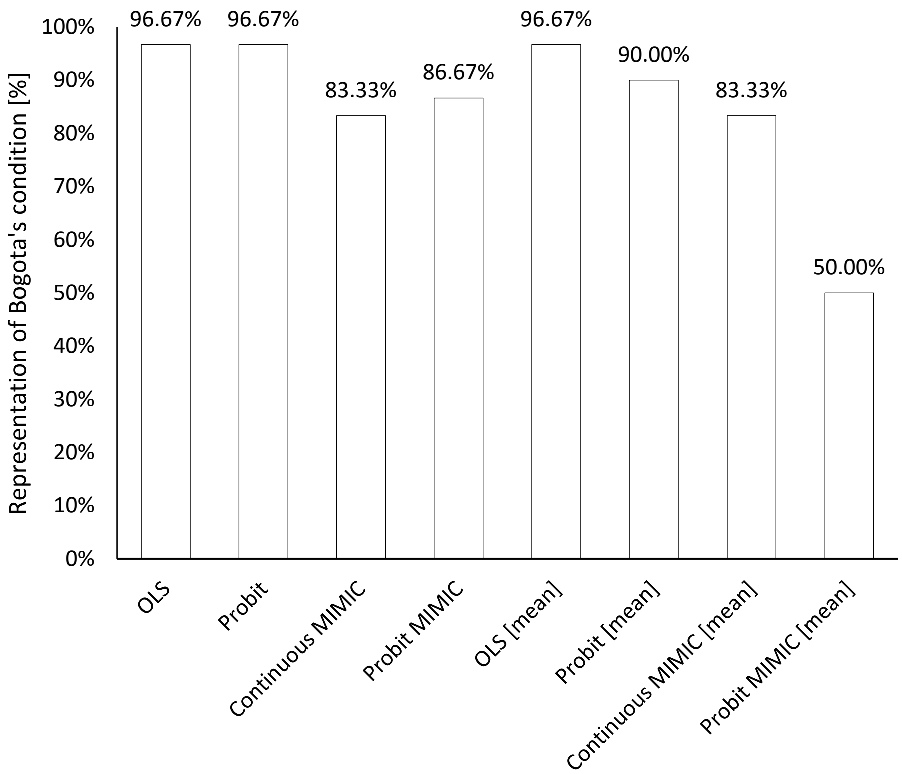

Figure 6.2. Match of the forecasting models with reported sidewalk QoS confidence interval

There are three approaches capable of predicting 29 out of 30 sidewalks (96.67%): OLS, ordered probit, and OLS mean (see Figure 6.2). Nonetheless, these models require the application of a field survey to obtain the information needed by some of the independent variables (see Table 6.1 and Table 6.2). On the other hand, there are four different approaches that do not use the pedestrian perceptions to forecast, but to infer the existence of latent variables and their relationship with objective attributes and, using this, then calculate the perceived QoS for the sidewalk using only the objective attributes. From these approaches, the expected value of the ordered probit MIMIC is able to predict 26 out of 30 sidewalks (86.67%) (see Figure 6.2 and Table 6.4).

However, the score is not the only indicator to be identified and analyzed to propose a QoS forecasting model. For this reason, the error variability obtained from the differences presented between the models' forecasted values and the perceived QoS for each sidewalk was also calculated (Figure 6.3).

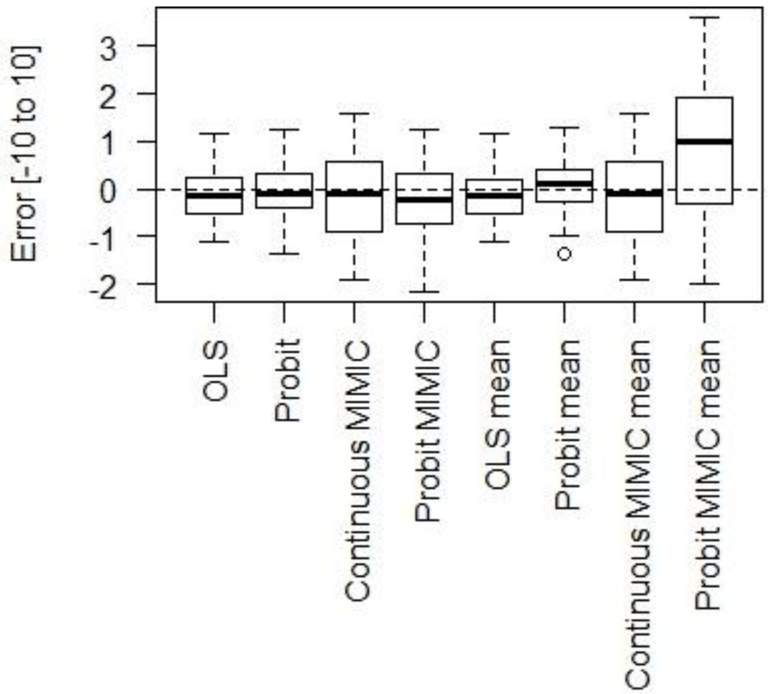

Figure 6.3. Sidewalks forecasting models' errors boxplot

Concerning errors, almost all the proposed models present an error variability of around 0% with a median close to 0. However, there are three approaches with a smaller less error variability and without outliers: OLS, Probit, and OLS mean. Nonetheless, these models require the application of a field survey to obtain the information needed by some of the independent variables (see Table 6.1 and Table 6.2). Of the approaches that do not need a survey applied, the expected value of the ordered probit MIMIC approach has the lowest interquartile range which means less variation in the errors (see Figure 6.3).

Finally, a χ^2 test was also proposed to verify if the distribution of the frequencies obtained using the different models were statistically similar to the distribution of the observed data frequency. The χ^2 test presents problems when the frequencies of the categories are less than 5. For this reason, to carry out this analysis four different categories were created for the SQoS (5 or less, 6, 7, 8 or more). The calculated test statistic must be compared with the critical value of χ^2 for a significance level of 0.05 and three degrees of freedom ($\chi^2 = 7.815$). The results for each approach are presented in Table 6.7.

Table 6.7. Statistical values of the χ^2 test for sidewalk QoS forecasting

Model approach	χ^2 statistical value
OLS	1.543
Probit	1.167
Continuous MIMIC	3.848
Probit MIMIC	1.281
OLS [mean]	1.543
Probit [mean]	4.944
Continuous MIMIC [mean]	3.848
Probit MIMIC [mean]	19.083

The frequency data distribution of the mean ordered probit MIMIC approach is not statistically similar to the distribution of the observed data frequency (see Table 6.7) and for this reason this model is rejected. However, the frequency distribution of the data of the other approaches are statistically similar to the frequency distribution of the observed data.

To select a model to predict the perceived SQoS for pedestrians, the three indicators presented previously (score, error variability, and χ^2 test) were used. Based on the results of these indicators and using MAUT, the best model to predict the SQoS is the ordered probit model through its expected value(see Table 6.8). However, as was previously mentioned, this model needs the application of pedestrian surveys as an input. Considering the models that do not use additional surveys the expected value of the ordered probit MIMIC model is the preferred specification (see Table 6.8).

Table 6.8. Performance indicator and MAUT comparison of QoS forecasting models

Approach	Match score	Error IQR	χ^2 statistical value	U	Position
OLS	96.67 %	0.740	1.543	0.974	3
Ord. Probit	96.67 %	0.687	1.167	0.993	1
Cont. MIMIC	83.33 %	1.443	3.848	0.683	6
Ord. MIMIC	86.67 %	1.035	1.281	0.844	5
OLS (m)	96.67 %	0.704	1.543	0.982	2
Ord. Probit (m)	90.00 %	0.655	4.944	0.882	4
Cont. MIMIC (m)	83.33 %	1.443	3.848	0.683	6
Ord. MIMIC (m)	50.00 %	2.184	19.083	0.000	8

The information presented in Table 6.2 can be used to forecast the SQoS using the ordered probit model. Equation (17), which is based on the information presented in Table 6.4, can be used to forecast the SQoS using the ordered probit MIMIC, assuming independent and normally distributed random errors with mean 0 and variance 1. The unobserved variable *z* for each sidewalk is obtained from Equation (17). Then, using these results and the thresholds presented in Table 6.4, the probability of obtaining each value (0 to 10) can be calculated. Then, using these probabilities, the expected value of the SQoS can be calculated using Equation (6).

$$z = 0.008 * A - 0.365 * BP - 0.315 * HP + 0.151 * MSP + 0.238 * SW + 0.096 * BW - 0.005 * DP \tag{17}$$

where

A: Average age of pedestrians using the sidewalk [years]
BP: Bicyclist present on the sidewalk [yes = 1 / no = 0]
HP: Potholes present on the sidewalk [yes = 1 / no = 0]
MSP: Median strip present on the sidewalk right of way [yes = 1 / no = 0]
SW: Sidewalk width [m]
BW: Buffer width [m]
DP: Driveway length on the sidewalk section [m]

The purpose of this chapter was to provide a forecasting model to predict the perceived SQoS. However, to carry out this analysis, it was necessary to predict some individuals' QoS perception. For this reason, models that can be used to forecast the pedestrian QoS are also provided, but with the consideration that these models were not designed for this purpose. Two of the indicators presented previously (error variability and χ^2 test) were used to select a model to predict the perceived QoS of pedestrians from the models described above (OLS, ordered probit, continuous MIMIC, and ordered probit MIMIC).

The error dispersion when predicting a specific QoS perceived by pedestrians was obtained from the differences presented between the models' forecasted values and the QoS perceived by pedestrians (Figure 6.4).

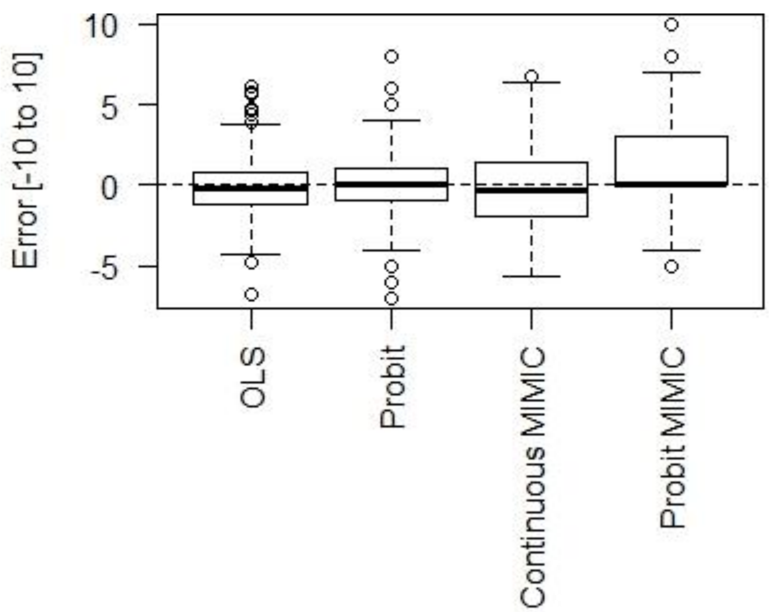

Figure 6.4. Pedestrians forecasting models' errors boxplot

Concerning errors, the proposed models present an error variability of around 0% with a median close to 0. However, there are two approaches with less error variability: OLS and ordered probit, where the ordered probit approach presents less outliers than the OLS. Nonetheless, in this case too, these models require the application of a field survey to obtain the information needed by some of the independent variables (see Table 6.1 and Table 6.2). Of the approaches that do not need a survey to be applied, the continuous and the ordered probit MIMIC approaches have a similar interquartile range value. However, the ordered probit MIMIC approach has more 0 error values considering that its first quartile and median are equal to 0 (see Figure 6.4).

A χ^2 test is also conducted to verify if the distribution of the frequencies obtained using the different models were statistically similar to the distribution of the observed data frequency. To carry out the analysis in this case, five different alternatives were proposed for the prediction of QoS perceived by pedestrians (0 and 1, 2 and 3, 4 to 6, 7 and 8, and 9 and 10). In this test, the calculated test statistic must be compared with a statistical value of the

χ^2 with a significance level of 0.05 and four degrees of freedom ($\chi^2 = 9.488$), to accept or reject the null hypothesis. The results of the test statistic for each approach are presented in Table 6.9.

Table 6.9. Statistical values of the χ^2 test for pedestrian QoS forecasting

Model approach	χ^2 statistical value
OLS	136.649
Probit	3.136
Continuous MIMIC	388.839
Probit MIMIC	116.743

Only the ordered probit approach can be considered to have a frequency distribution of the expected data that is statistically similar to the frequency distribution of the observed data (see Table 6.9). In addition, for the reason previously presented all the other models have to be rejected. The only accepted approach requires the application of a field survey to obtain the information needed by some of the independent variables (see Table 6.2). In addition, to ask about the perceived QoS for an individual pedestrian using the ordered probit, needs to consider a regrouped scale (0 and 1, 2 and 3, 4 to 6, 7 and 8, and 9 and 10) to be answered for the surveyed.

7. Discussion and analysis

The oldest, most widely accepted, and most popular service indicator is the LOS. Initially, LOS methods (developed for motorized traffic) considered only attributes related to the flow-capacity relationship (Roess & Prassas, 2014; Transportation Research Board, 1965). The first methodologies developed to calculate PPSI were based on the LOS indicator that considered only on-site measurable attributes related to the flow-capacity relationship. In the following years, it evolved into a new manner that considered other on-site measurable attributes, creating methodologies with better PPSI predictive power. Then, the most-recently proposed evolution is that which considers the perceptions of experts to calculate the perceived PPSI (see Table 4.5). However, expert judgement-based methodologies appear least in the literature, despite having the best PPSI predictive power (see Table 4.5). For this reason, considering the users' (pedestrians') perceptions for methodologies that try to explain or predict the QoS can result in better transportation infrastructures for pedestrians.

The results strongly suggest that PPSI methodologies are site-specific. The poor performance in explaining the perceived QoS (maximum 50% of the locations) suggest that methods need to be calibrated for the specific town or city. In fact, the official PLOS method for Bogota (Alcaldia Mayor de Bogota D.C., 2005) which is a calibrated version of the method used by the Transportation Research Board (2000) increases its performance by 23.34 percentage points because of this calibration (see Table 4.4). All the methodologies used for this study were developed to evaluate the PPSI on the sidewalk link without considering their intersections. Out of the 28 methodologies evaluated in the 30 locations in Bogotá, 22 of them use objective measurable variables. Out of these 22, 36% use attributes related to the flow-capacity relationship and so data can be gathered from a short visit to where the different tallies have to be made. The remaining 64% use objective attributes of the sidewalk and their surroundings, where most of the information needed can be gathered from on-site measurements. There are six methodologies that need the evaluation of experts or subjective information about the sidewalks to be applied.

The user perception inputs are one of the least studied in terms of its capacity to explain the QoS perception by pedestrians, despite the fact that perception variables contribute most to the variance explanation of the perceived QoS (see Figure 5.1, Figure 5.2, Figure 5.3, and Figure 5.4). This result matches that outlined by Fernández-Heredia et al. (2016) in terms of improving the chosen model's performance by considering perceptions. In this study, it can be suggested that when perceptual variables are not considered, the models' performance in terms of variance explanation decreases sharply in comparison with the models containing user-perception variables (see Figure 5.1, Figure 5.2, Figure 5.3, and Figure 5.4). In addition, the results suggest that perceptual variables explain more variance in the perceived QoS, regardless of the grouping decision or the order of addition of perceptions to the models, as they variance explanation never overlap the other variables' variance explanation (see Table 5.3, Table 5.5, and Table 5.7).

The other groups of variables used to explain the perceived QoS, namely environmental, sociodemographic, and physical variables, have a lower contribution to the variance explanation of the perceived QoS in comparison with the perceptual group of variables. In addition, in terms of perceived QoS variance explanation, there are no differences between these group of variables. Initially, the variance explanation of the perceived QoS of the physical and sociodemographic variables overlap when they are used as independent variables (see Table 5.6 and Table 5.7). However, the maximum variance explanation value generated by the use of the physical variables is greater than that generated by the sociodemographic variables (see Table 5.6), which supports the idea that comparing these two groups of variables the methodologies for the calculation of PPSI based on physical sidewalk attributes are better (see Table 4.5). In addition, the overlapping of the variance explanation can be also seen when the sociodemographic and environmental attributes' values are compared (see Table 5.6 and Table 5.7). In this case, the maximum variance explanation value generated by the use of sociodemographic attributes is greater than that generated by the environmental attributes (see Table 5.6). However, this overlapping is significantly different from the physical and perceptual attributes' values, which means that sociodemographic and environmental groups of variables can be considered to contribute less to the variance explanation of the perceived QoS when the other group of inputs play a part in the explanation (see Table 5.7).

Considering the power of users' perceptions to explain the perceived QoS, much more information can be extracted and analyzed from perceptions to better understand QoS. To uncover latent variables from users' perceptions is an approach that identifies the intangible variables' influence on the perceptions (Ortúzar & Willumsen, 2011). The first step in proposing the existence of latent variables is to develop an exploratory factor analysis (EFA). The advantage of using EFA is the possibility of determining which perception attributes share common variance-covariance characteristics. Then, using a confirmatory factor analysis (CFA) the hypothesis developed from the EFA can be tested to confirm the existence of a latent variable and its perception indicators (Schumacker & Lomax, 2004). For this study, it is possible to specify the number of latent variables and indicators from the CFA results to identify a theoretical model that can be used or applied in different contexts. A very recent paper by Geetha Rajendran Bivina & Parida (2019) provided a latent variable approach based on user perceptions that identified four latent variables that positively influence the PLOS. The results of the present research also identified the positive effects discovered by Geetha Rajendran Bivina & Parida (2019), but in addition, identified three latent variables that negatively influence the perceived QoS.

There are two latent variables that are initially perceived by pedestrians when walking that affects their perception of the QoS: *bike hassles* and *amenities* (see Figure 5.5). The *bike hassles* explains the pedestrians' perception of bike speed and flow in both directions (see Table 5.11). In the literature it can be found that the interaction of pedestrians with bicycles on their infrastructure decreases the QoS that an infrastructure renders (Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Sahani et al., 2017). However, the negative impact generated by the *bike hassles* on the perceived QoS is not direct, and needs the mediation of other latent variables (see Figure 5.5). On the other hand, the *amenities* explains the pedestrian's perception of the presence of restrooms, shops, and shade on the sidewalk, positively impacting the perceived QoS through the mediation of other latent variables. This result is supported in the literature, where it is established that the presence and good quality of public restrooms on sidewalks positively impacts the *amenities*, generating a better QoS for a sidewalk (Motamed & Bitaraf, 2016). In addition, the presence of shops on the infrastructure or close to the infrastructure provide a safe and secure sidewalk (Motamed & Bitaraf, 2016) where people are more likely to walk

(Choi et al., 2016; Pikora et al., 2003). Finally, the presence of shade on the sidewalks also contributes to an increase in pedestrian comfort when walking (Jaskiewicz, 1999) and improves the visual quality of the environment (Macdonald et al., 2018).

Externalities helps to mediate the effect of *bike hassles* and *amenities* on the perceived QoS. This latent variable explains the pedestrian's perception of the road width, number of vehicular lanes, HGV flow, vehicular speed, and noise, negatively impacting the perceived QoS through the mediation of other latent variables (see Table 5.11 and Figure 5.5). This result is supported in the literature, where it is explained that the interaction of pedestrians with traffic attributes like heavy goods vehicle (HGV) flow generate an increase in stress levels, decreasing the pedestrian LOS (Mozer, 1994). In addition, when pedestrians interact with high vehicular speeds, an increase in stress levels is also evidenced which affects their experience (Mozer, 1994), decreasing the perceived pedestrian safety (Jaskiewicz, 1999; Landis et al., 2001; Motamed & Bitaraf, 2016; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015), PLOS (S. Kim et al., 2013; Landis et al., 2001; Mozer, 1994; Sahani et al., 2017; State of Florida Department of Transportation, 2009), level of comfort (Pikora et al., 2003), and satisfaction (Jensen, 2007). The literature also mentions that vehicle infrastructure characteristics like wide roads and a high number of lanes increase pedestrian stress levels (Macdonald et al., 2018; Mozer, 1994), and decrease pedestrian satisfaction (Choi et al., 2016; Jensen, 2007). However, these interactions do not take place only between pedestrians and geometric and traffic variables, there is also an interaction with noise levels on the sidewalk that decreases perceived pedestrian pleasure (Motamed & Bitaraf, 2016), the QoS for pedestrians (Sarkar, 2003) and the PLOS (Christopoulou & Pitsiava-Latinopoulou, 2012) when the noise level increases.

One of the latent variables that helps to mediate the negative effect of *externalities* on the perceived QoS is the *discomfort*. This latent variable explains the pedestrian's perception of interaction with other pedestrians and the perceived stress on the infrastructure, negatively impacting the perceived QoS through the mediation of other latent variables (see Table 5.11 and Figure 5.5). This result is supported by the literature, which states that, over time, pedestrian interaction with other pedestrians decreases their PLOS (Asadi-Shekari et al., 2013; Banerjee et al., 2018). In addition, stress levels are understood to move in the opposite direction to the PLOS. In other words, when stress levels go up, the PLOS goes down (Mozer, 1994).

Another latent variable that helps to mediate the effect of *discomfort*, *externalities*, *bike hassles*, and *amenities* on the perceived QoS is *protection*. This latent variable explains the pedestrian's perception of protection in terms of safety and security on a sidewalk, and it positively impacts the perceived QoS through the mediation of other latent variables (see Table 5.11 and Figure 5.5). This result is supported in the literature, where it was found that increasing the level of safety (Christopoulou & Pitsiava-Latinopoulou, 2012; Ewing et al., 2006; Pikora et al., 2003) and security (G. R. Bivina et al., 2018; Gallin, 2001; Motamed & Bitaraf, 2016) also increased pedestrian QoS.

Similarly, the *surroundings* also helps to mediate the effect of *protection*, *discomfort*, and *externalities* on the perceived QoS. This latent variable explains the pedestrian's perception of the weather, lighting, odor, environment, cleanliness, and landscape present on a sidewalk, and positively impacts the perceived QoS both directly and through the mediation of the *sidewalk characteristics* (see Table 5.11 and Figure 5.5). This result is supported in the literature, where it is initially explained that bad weather conditions like rain can cause pedestrians to express negative attitudes (Kang & Fricker, 2016). In addition, the improvement of built environment characteristics like a good sidewalk environment and landscape increases the perceived pedestrian comfort (T. Kim et al., 2011) and satisfaction (Jensen, 2007). The literature also mentions that there are some characteristics of the sidewalk surroundings like good lighting that also increases the perceived sidewalk PLOS (Kang et al., 2013). In addition, having a clean sidewalk with a pleasant odor can also increase the quality of the sidewalk (Motamed & Bitaraf, 2016; Pikora et al., 2003) and improve the pleasure experienced by pedestrians (G. R. Bivina et al., 2018).

Finally, the *sidewalk characteristics* also helps to mediate the effect of *surroundings*, *protection*, *discomfort*, and *externalities* on the perceived QoS. This latent variable explains the pedestrian's perception of the sidewalk width, condition, furniture, trees, signage, and the public transport access, directly and positively impacting the perceived QoS (see Table 5.11 and Figure 5.5). These results are supported in the literature, which state that, over time, an increase in the width of a sidewalk increases PLOS (Asadi-Shekari et al., 2013; Banerjee et al., 2018). However, this geometry attribute is not the only one to consider when trying to understand the sidewalk QoS by considering the sidewalk characteristics. The interaction of pedestrians with elements of the sidewalk like the presence of good furniture improve pedestrian comfort (Sarkar, 2003) and pleasure (Motamed & Bitaraf, 2016) when walking. In addition, the presence of trees on the sidewalk increases pedestrian satisfaction (Jensen, 2007), PLOS (Christopoulou & Pitsiava-Latinopoulou, 2012; Talavera-Garcia & Soria-Lara, 2015), and generate a more attractive infrastructure for walking (Choi et al., 2016; Motamed & Bitaraf, 2016). Also, the presence of good pedestrian signaling and support facilities that aid pedestrians increase the PLOS (Gallin, 2001) and sidewalk QoS (T. Kim et al., 2011). However, the fact that sidewalks have the previously mentioned elements is not enough, they, and the sidewalk, must also be in good condition to provide a better infrastructure for pedestrians (G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999; T. Kim et al., 2011; Marisamynathan & Lakshmi, 2016; Motamed & Bitaraf, 2016; Pikora et al., 2003; Sarkar, 2003). Lastly, the access to public transport on a sidewalk also increases the sidewalk PLOS (Christopoulou & Pitsiava-Latinopoulou, 2012) and satisfaction (Choi et al., 2016), providing a more attractive sidewalk to walk on (Pikora et al., 2003).

All the previously mentioned effects, both direct and mediated, affect the pedestrian perception of the QoS when walking. There are four different latent variables that generate a positive effect on the perceived QoS: *sidewalk characteristics*, *surroundings*, *protection*, and *amenities*. Of these latent variables, the one that generates the greatest positive effect on the perceived QoS is *sidewalk characteristics*. This effect is direct only and is understandable because this latent variable relates to the direct interaction of the pedestrian with the infrastructure. However, in order to increase the perception of the QoS is not enough to provide a sidewalk with good characteristics. It is also necessary to build a sidewalk where pedestrians can perceive good surroundings, protection against crime and accidents, and the presence of places to interact with. On the other hand, there are three different latent variables that negatively impact the perceived QoS: *discomfort*, *externalities*, and *bike hassles*. In general, these three latent variables express the way that pedestrians interact with other transportation modes including other pedestrians. The *externalities*, which considers the interaction of pedestrians with non-active modes, generates the greatest negative effect on the perceived QoS. Then, *discomfort*, which considers the interaction of pedestrians with other pedestrians, generates the second greatest negative effect on the perceived QoS. Finally, *bike hassles* which considers the interaction of pedestrians with cyclists, generates the lowest negative effect on the perceived QoS (see Table 5.14).

The previous paragraphs explain the ways in which pedestrians perceive the QoS when walking on an urban sidewalk by considering their perceptions. This knowledge can contribute to understanding why and how pedestrians quantify the QoS. However, it is also useful for knowing which user and sidewalk attributes have effects on the perceived sidewalk QoS (SQoS). To select a forecasting model for the perceived SQoS and QoS, three different performance indicators were used: match score, error variability, and the χ^2 test. As was mentioned in the previous chapter, the model selected was the expected value of the ordered probit to predict the perceived SQoS and QoS (Table 6.2). However, because of the difficulties applying this model to real-life conditions due to the need to carry out surveys, the expected value of the ordered probit MIMIC model was also selected to calculate only the perceived SQoS (Table 6.4). In addition, the choice of the ordered models like the ones selected is also supported in the literature where the use of this approximation is suggested for trying to understand the QoS (Eboli & Mazzulla, 2010). In both cases, for sidewalk forecasting, the expected value of each model was selected because the SQoS is considered to be a continuous value. In the case of the perceived QoS forecasting the ordered probit model is used to select the most probable value as the perceived QoS.

Considering the forecasting ordered probit model, 16 independent variables were identified that contribute to the prediction of the SQoS and the perceived QoS. From these independent variables, 11 are users' perceptions and only five are characteristics of the users and sidewalks. This finding is not surprising because the literature manifests that the models' performance improves when users' perceptions are included in them (Fernández-Heredia et al., 2016). Some of the perception independent variables improve the perceived SQoS and QoS that consider how positively pedestrians perceive sidewalk elements (sidewalk surface condition, horizontal marking, sidewalk furniture, organized spaces, and tree presence), the sidewalk surroundings (building articulation, road safety, and lighting), and geometry aspects of the sidewalk (sidewalk width). On the other hand, there are also perceptual independent variables that decrease the perceived SQoS and QoS that considers the pedestrians' irritation caused by other transportation modes (heavy good vehicles and vehicular flow close to pedestrians). Considering the independent variables consisting of characteristics of the sidewalk, this model suggests that providing bus stops and restrooms on sidewalks increases the perceived SQoS and QoS. On the other hand, on sidewalks where the length of driveways and noise increase, the perception of the SQoS and QoS decrease. Finally, considering user characteristics as independent variables, this model suggests that the older the user, the better the perception of the SQoS and QoS (see Table 6.2).

From the ordered probit model the contribution of objective and subjective independent variables to the QoS forecasting can be compared. The absolute effect of the subjective independent variables on the unobserved value *z* represents 65% of the total effect and the remaining 35% of the effect it is attributed to the objective independent variables. This effect is similar to that found when comparing the variability explanation of the perceived QoS using perceptions. Additionally, the necessity of including perceptions to increase understanding of pedestrian perception of the QoS when walking is reinforced.

Turning to the forecasting ordered probit MIMIC model, 11 independent variables that contribute to the prediction of the SQoS were identified. Of these independent variables, 7 are user and sidewalk characteristics. In addition, 4 are latent variables that were previously discussed and analyzed (*sidewalk characteristics*, *surroundings*, *discomfort*, and *externalities*). The use of latent variables in these kinds of models allows this phenomenon to be approached with the consideration of both the objective and subjective variables (Eboli & Mazzulla, 2015). In this case, using the sidewalk and user characteristics each latent variable and subsequently the perceived SQoS are explained (see Table 6.4).

The *externalities* is the first to be perceived by pedestrians when walking, negatively impacting the perceived SQoS with the mediation of the other latent variables (*discomfort*, *surroundings*, and *sidewalk characteristics*). To predict the value of this latent variable, the ordered probit MIMIC model suggests that sidewalks with the presence of bicyclists increases the latent variable value, decreasing the perceived SQoS. This suggestion is supported in the literature, where it is established that the presence of bicycles on sidewalks negatively impact the perceived PLOS (Dandan et al., 2007; Kang et al., 2013). In addition, this model also suggests that sidewalks located along rights of way and that have a median strip which increases the separation between pedestrians and motor vehicles can counteract the effects of the *externalities* on the perceived SQoS. These results are supported in the literature where it is established that the presence of a median strip along the right of way improves the satisfaction of pedestrians because of the controlling effect of this element on the motor vehicles (Jensen, 2007). In addition, an increase in the separation between pedestrians and motor vehicles has been identified over time to have an effect that improves the PLOS (Asadi-Shekari et al., 2013; Banerjee et al., 2018).

The second latent variable that the ordered probit MIMIC model suggests that pedestrians perceive when walking is *discomfort*. This latent variable also negatively impacts the perceived SQoS with the mediation of other latent variables (*surroundings* and *sidewalk characteristics*). This latent variable is impacted by the *externalities*, which means that the sidewalk characteristics affecting the *externalities* also indirectly affect the *discomfort*. However, the present study was not able to find which sidewalk or user characteristics can directly impact the value of this latent variable.

The third latent variable that the ordered probit MIMIC model suggests that pedestrians perceive when walking is *surroundings*. This latent variable positively and directly impacts the perceived SQoS and with the mediation of the *sidewalk characteristics*. In addition, this latent variable is negatively impacted by the *externalities* and *discomfort*, which means that bike presence, median strip presence, and buffer width indirectly impact this latent variable. However, the ordered probit MIMIC model suggests that not only the buffer width indirectly impacts this latent variable, but also an increase of the separation between pedestrians and motor vehicles directly impacts this latent variable and improves its value. In addition, the ordered probit MIMIC model also suggests that increasing the length of driveways along the sidewalk decreases the perception of the *surroundings* for pedestrians, negatively impacting the perceived SQoS. This result is supported by the literature, where it is established that the presence of driveway segments increases conflicts for pedestrians (Gallin, 2001; Petritsch et al., 2006), creates potential dangers for them (Mozer, 1994), and reduces their satisfaction (Choi et al., 2016), comfort, and safety (Dandan et al., 2007).

The fourth and last latent variable that the ordered probit MIMIC model suggests that pedestrians perceive when walking is the *sidewalk characteristics*. This latent variable also positively impacts the perceived SQoS and it does so only in a direct way. In addition, this latent variable is impacted by the other latent variables (*surroundings*, *discomfort*, and *externalities*). This means that the attributes buffer width, driveway length, median strip presence, and bike presence indirectly impact this latent variable. In addition, the ordered probit MIMIC model suggests that some characteristics of the sidewalk like the presence of potholes can decrease the latent variable value, negatively impacting the perceived SQoS. This finding can be supported in the literature that states that a sidewalk in bad condition represented by the presence of potholes decreases the infrastructure quality (G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999; T. Kim et al., 2011; Marisamynathan & Lakshmi, 2016; Motamed & Bitaraf, 2016; Pikora et al., 2003; Sarkar, 2003). In addition, this model also suggests that increasing other sidewalk characteristics like sidewalk width improve the latent variable value and the perceived SQoS, which is consistent with what has been developed in the literature over time (Asadi-Shekari et al., 2013; Banerjee et al., 2018). In addition, this model also suggests that a user characteristic like user age also impacts the latent variable value in a positive way, which means that the older the user the better the value for the latent variable and the perceived SQoS.

All the previously mentioned latent variables (*sidewalk characteristics*, *surroundings*, *discomfort*, and *externalities*) affect the perceived SQoS both directly and indirectly. This means that the attribute user age and the sidewalk attributes pothole presence, sidewalk width, buffer width, driveway length, median strip presence, and bike presence indirectly affect the perceived SQoS. However, the ordered probit MIMIC model suggests that the bicyclist presence not only indirectly impacts the perceived SQoS, but also the presence of bicyclists on the sidewalk directly and negatively impacts the perceived SQoS. In addition, improving the perception of the *sidewalk characteristics* and *surroundings* generates a positive impact on the perceived SQoS. In addition, removing the nuisances that pedestrians perceive from *discomfort* and *externalities*, also improves the perceived SQoS. These improvements and neutralizations can be developed by considering and improving the different sidewalk attributes identified previously (see Table 6.4).

From the results of this study, the performance of different methodologies to calculate PPSI found in the literature were tested. From this analysis, it was possible to establish that methodologies using expert judgment to calculate the PPSI better represent the local conditions of the city of Bogotá (see Table 4.5). However, without proper calibration, the different methodologies do not perform well when directly applied to the city of Bogotá (see

Table 6.5). Nonetheless, the results on the use of perceptions from experts could be used as a base to continue the research and explore this direction more. The first step was to establish the role and impact of users' perceptions when attempting to calculate the perceived QoS. From this step, it can be suggested that for pedestrians' QoS the most important attributes to consider are their perceptions (see Table 5.7). The second step was to understand how pedestrians perceive their QoS through the development of a perceived QoS cognitive map (see Table 5.14 and Figure 5.5). Once this cognitive map was developed it could be used as a tool to understand which of the attributes present when pedestrians walk on urban sidewalks impact their perception of the QoS. In addition, this cognitive map also serves as a tool to make choices about what characteristics should be improved, and how to intervene to improve the perceived QoS. Finally, considering the importance of users' perceptions, two models were developed in this study to forecast the perceived SQoS and QoS (see Table 6.2 and Table 6.4). These models can be used to define the perceived SQoS of the different sidewalks for the city of Bogotá, with the consideration of basic entry data about each sidewalk, their users, and their rights of way.

8. Conclusions, recommendations, and further research

8.1 Conclusions

Despite the steady and continuous evolution of indicators and methods to evaluate the service or performance of pedestrian infrastructure, over recent decades, methods have not been developed into new concepts that improve explanatory and forecasting results. The fact that expert-judgement methods were proved to produce the best outcomes in Bogotá, together with the poor performance of the majority of existing methodologies, gave an insight into the discovery that person-oriented models are quite convenient.

When the PPSI on urban sidewalks must be evaluated using existing methodologies, it is highly recommended that the methodologies be calibrated for the specific place or context. This suggestion is based on the results of this study where the Alcaldia Mayor de Bogota D.C. (2005) methodology was calibrated before its application, generating an increase on the forecasting ability in comparison with the methodology on which it was based (Transportation Research Board, 2000) (see Table 4.4).

This dissertation provides solid evidence for the relevance of user input when assessing the service or the performance of a segment (linear) pedestrian infrastructure, which can be added to the models as independent variables (through the development of OLS or ordered models) or as latent variables indicators (through the development of SEM or MIMIC models). Perceptions, which are subjective responses based on different peoples' answers for the same attribute, substantially increase the explanation of the QoS assigned by pedestrians to an urban sidewalk. Unlike a highway, where drivers care about flow-capacity attributes (speed and delays) that allow them to complete their trip as fast as possible, walkers interact with the open environment, with the city, and with other modes, making the framework for PPSI more complex than for other modes.

A major conclusion of this research is the identification of the sources of QoS on urban sidewalks. These sources were mapped on a cognitive map that can be used to identify them clearly. From this cognitive map, four latent variables were found to impact the perceived QoS in a positive way. It was also established that the pedestrian's perception of *sidewalk characteristics* (latent variable) improves the perceived QoS the most. For this reason, increasing the quality of the sidewalk characteristics (width, condition, furniture, trees, public transport access and signage) must be a priority in the improvement of urban sidewalks. In addition, it is not recommended that the positive effect of other latent variables be omitted, as these also positively impact the perceived QoS. This means that to improve the pedestrian infrastructure, perceptions of the *surroundings* (weather, lighting, odor, environment, cleanliness, and landscape), *protection* (security, sidewalk safety and road safety), and *amenities* (restrooms, shops, and shade) need also be improved.

On the other hand, three latent variables related to the interaction between pedestrians and other transportation modes negatively impact the perceived QoS. The first, *externalities*, represents the interaction between pedestrians and non-active modes and has the greatest negative impact on the perceived QoS. Counteracting the negative effect of *externalities* on pedestrians should result in an improvement of the perceived QoS. This counterbalance can be generated in two different ways: (i) by improving the pedestrian's perception of the amenities (restrooms, shops, and shade), and (ii) by decreasing the negative effect of this latent variable with the design of rights of way with less space for non-active vehicles (narrower vehicular roads with less lanes), and regulating the heavy goods vehicle (HGV) flow, vehicular speed, and noise. However, it is highly recommended that both counteracting actions are applied simultaneously. In addition, it is also recommended that the negative impact of the other latent variables related to the interaction of pedestrians with bicyclists (*bike hassles*) and with other pedestrians (*discomfort*) be also considered. To decrease the negative impact caused by bicyclists, it is recommended that their flow and speed close to pedestrians be regulated, to improve the pedestrian's perceptions of this hassle. In addition, to decrease the negative impact caused by the interaction between pedestrians themselves (*discomfort*) the recommendation is to design and develop more spaces that can be used for walking, reducing pedestrian density and the potential for conflict between them.

Once the importance of perceptions in the explanation of the perceived QoS was identified, the next step was to develop a methodology to predict the SQoS for urban sidewalks in Bogotá. To accomplish this objective, four different approximations (OLS, ordered probit, continuous MIMIC, and ordered probit MIMIC) were used. The results recommend the use of ordered models considering that they have better goodness of fit indicators and reproduce the observed data distribution better. In addition, in the literature, the ordered models are recommended most highly for service quality investigations.

The resulting forecasting models restate the importance of perceptions in the explanation of the perceived SQoS and QoS. This affirmation can be supported by fact that the perceptual independent variables explain the SQoS and QoS variance in the models better. In addition, the role and impacts of some sidewalk characteristics are suggested by the forecasting models (see Table 6.2 and Table 6.4). Initially, these models suggested that the presence of bicyclists on the sidewalk directly impacts the perceived SQoS and increased the negative effect of *externalities* in the perceived SQoS. In addition, increasing the separation between pedestrians and the road directly counteracts the negative effect of *externalities* and improves the perception of *surroundings*. Also, designing rights of way that include median strips counteracts the negative effect of the externalities on the perceived SQoS and QoS. Similarly, building sidewalks with reduced driveway length will impact positively on the perception of *surroundings*. Also, sidewalks without potholes and increased width, impact positively on the pedestrian perception of *sidewalk characteristics*. In conclusion, it is possible to change on-site attributes and perceptions to generate better pedestrian infrastructure and to improve the local representation of an SQoS and QoS model.

8.2 Recommendations and further research

Considering that this study was limited, this section will outline some of the recommendations for developing further research on this topic. Initially, to understand the complete panorama of the different PPSI and their effects on pedestrians' impressions, a study that considers the different ways in which pedestrians perceive the PPSI (comfort, pleasure, stress, experience, and satisfaction) should be developed. In this research, it is highly recommended to understand the differences between each element stated by pedestrians when they are asked to rate each of these terms. For this, a cognitive map explaining how pedestrians understand each term could be also useful for improving knowledge about pedestrians and how to build better urban sidewalks for them.

In this study two SQoS forecasting methodologies were proposed, however, these methodologies were designed for Bogotá only. Considering the structure of the ordered probit MIMIC it is possible to develop a methodology to calibrate this model for its use in a different context. The first approach for developing this calibration methodology may consist of understanding the way that the measurement model (users' perceptions) is generated in the new context. Then, by considering the differences between the proposed measurement model and the one in the new context, a calibration method can be proposed. Also, there are potential in the use of artificial intelligence to obtain the needed information from images to objectively apply the forecasting methodology.

In addition, the methodology that the present study proposed for the calculation of the perceived QoS requires pedestrian interception surveys and so this methodology was not part of the scope of this research. For this reason, it is highly recommended to develop a latent variable methodology that can be applied using only on-site measurable attributes to forecast the pedestrian QoS. Once this methodology is proposed, it has to be tested in terms of goodness of fit indicators and data generation distribution. The purpose of creating a methodology that can be applied only with on-site measurable attributes is to speed up the process for practitioners.

Finally, this study makes one of the first attempts to understand pedestrians' perceptions and this topic is still nascent. It only provides information about pedestrians considered as a transportation mode. For this reason, it is recommended that more studies be developed that contemplate the heterogeneous effects of pedestrians by consider their differences (e.g., sex, occupation, etc.) and the interactions with their surroundings that can exist because of these differences.

9. References

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10. Appendix A – Sidewalk sample

Sidewalk # 1 (Carrera 9 between Calle 72 and 73)

- 
Facade separation distance: 7.77 m
- Sidewalk length: 121.2 m
- Discontinuities length: 78.50 m
- Driveways length: 14.7 m
- Transparencies length: 121.20 m
- Roof length: 0.00 m

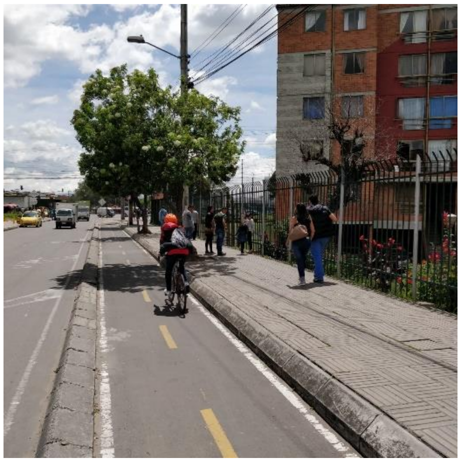
- Sidewalk width: 2.73 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 4.10 m
- Lanes width: 11.70 m
- Road width: 11.70 m
- Shoulder width: 0.00 m
- Buffer width: 2.26 m
- Buffer: on-street parking
- Speed limit: 30 km/h
- Trees number: 3
- Lanes number: 3
- Conflicts number: 3
- Restrooms number: 2
- Bus stop number: 0
- Ramps number:2
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: yes
- Interferences: medium

Sidewalk # 2 (Calle 9 between Carrera 3 east and 1)

- 
Facade separation distance: 0.00 m
- Sidewalk length: 127.7 m
- Discontinuities length: 0.00 m
- Driveways length: 6.7 m
- Transparencies length: 0.00 m
- Roof length: 35.30 m

- Sidewalk width: 3.80 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.45 m
- Lanes width: 3.45 m
- Road width: 3.45 m
- Shoulder width: 0.00 m
- Buffer width: 0.00 m
- Buffer: no buffer
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 3
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: no
- Interferences: low

Sidewalk # 3 (Carrera 104 between diagonal 16 and 16B)

- 
  Facade separation distance: 3.93 m
- Sidewalk length: 61.8 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 61.80 m
- Roof length: 0.00 m

- Sidewalk width: 2.65 m
- Bicycle infrastructure width: 1.90 m
- Exterior lane width: 2.80 m
- Lanes width: 2.80 m
- Road width: 8.70 m
- Shoulder width: 3.20 m
- Buffer width: 2.50 m
- Buffer: elements
- Speed limit: 30 km/h
- Trees number: 4
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: yes
- Median street presence: no
- Potholes presence: yes
- Interferences: medium

Sidewalk # 4 (Calle 19 between Carrera 4 and 5)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 163.1 m
- Discontinuities length: 60.3 m
- Driveways length: 9.0 m
- Transparencies length: 20.75 m
- Roof length: 89.65 m

- Sidewalk width: 4.92 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.45 m
- Lanes width: 10.10 m
- Road width: 25.40 m
- Shoulder width: 0.27 m
- Buffer width: 2.22 m
- Buffer: elements
- Speed limit: 30 km/h
- Trees number: 14
- Lanes number: 3
- Conflicts number: 2
- Restrooms number: 2
- Bus stop number: 2
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: no
- Interferences: high

Sidewalk # 5 (Carrera 13 between calle 63 and 62)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 63.6 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 17.10 m
- Roof length: 47.90 m

- Sidewalk width: 2.06 m
- Bicycle infrastructure width: 2.04 m
- Exterior lane width: 3.20 m
- Lanes width: 9.10 m
- Road width: 9.40 m
- Shoulder width: 0.20 m
- Buffer width: 3.52 m
- Buffer: elements
- Speed limit: 30 km/h
- Trees number: 3
- Lanes number: 3
- Conflicts number: 0
- Restrooms number: 1
- Bus stop number: 0
- Ramps number: 2
- Bicycle infrastructure presence: yes
- Median street presence: no
- Potholes presence: yes
- Interferences: high

Sidewalk # 6 (Av. Suba between Carrera 99B and 101)

- 
  Facade separation distance: 14.96 m
- Sidewalk length: 111.1 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 111.10 m
- Roof length: 0.00 m

- Sidewalk width: 2.48 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.00 m
- Lanes width: 6.20 m
- Road width: 30.40 m
- Shoulder width: 0.19 m
- Buffer width: 1.42 m
- Buffer: elements
- Speed limit: 60 km/h
- Trees number: 9
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: yes
- Interferences: medium

Sidewalk # 7 (Tv. 94 between calle 80D and 81A)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 85.4 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 6.00 m
- Roof length: 75.50 m

- Sidewalk width: 3.78 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.80 m
- Lanes width: 11.40 m
- Road width: 11.40 m
- Shoulder width: 0.00 m
- Buffer width: 2.04 m
- Buffer: on-street parking
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 2
- Bus stop number: 0
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: no
- Interferences: high

Sidewalk # 8 (Calle 80 between Carrera 76 and 73A)

- 
  Facade separation distance: 12.84 m
- Sidewalk length: 93.6 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 93.60 m
- Roof length: 0.00 m

- Sidewalk width: 2.59 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.50 m
- Lanes width: 10.00 m
- Road width: 45.70 m
- Shoulder width: 0.14 m
- Buffer width: 1.42 m
- Buffer: elements
- Speed limit: 60 km/h
- Trees number: 11
- Lanes number: 3
- Conflicts number: 0
- Restrooms number: 1
- Bus stop number: 1
- Ramps number: 2
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: yes
- Interferences: low

Sidewalk # 9 (Calle 134 between Carrera 53C and 54)

- Facade separation distance: 10.25 m
- Sidewalk length: 68.0 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 68.00 m
- Roof length: 0.00 m

- Sidewalk width: 2.70 m
- Bicycle infrastructure width: 2.70 m
- Exterior lane width: 2.90 m
- Lanes width: 5.80 m
- Road width: 15.60 m
- Shoulder width: 0.30 m
- Buffer width: 4.10 m
- Buffer: no elements
- Speed limit: 60 km/h
- Trees number: 5
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 2
- Bicycle infrastructure presence: yes
- Median street presence: yes
- Potholes presence: yes
- Interferences: low

Sidewalk # 10 (Carrera 3 between calle 12C and 12D)

- Facade separation distance: 0.00 m
- Sidewalk length: 81.6 m
- Discontinuities length: 40.75 m
- Driveways length: 3.2 m
- Transparencies length: 0.00 m
- Roof length: 49.60 m

- Sidewalk width: 0.98 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 2.60 m
- Lanes width: 2.60 m
- Road width: 2.60 m
- Shoulder width: 0.00 m
- Buffer width: 0.00 m
- Buffer: no buffer
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 2
- Restrooms number: 2
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: yes
- Interferences: medium

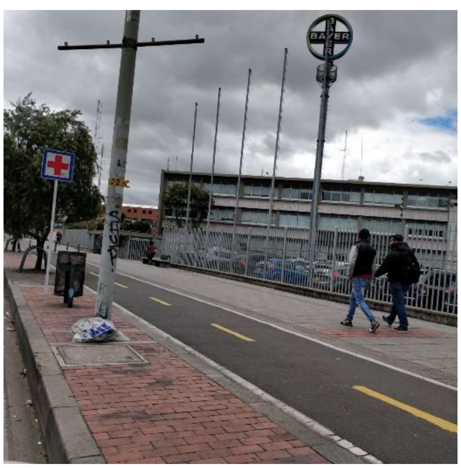
Sidewalk # 11 (Carrera 70 between calle 74C and 73A)

- 

Facade separation distance: 0.00 m
- Sidewalk length: 147.2 m
- Discontinuities length: 2.90 m
- Driveways length: 55.7 m
- Transparencies length: 44.40 m
- Roof length: 52.20 m

- Sidewalk width: 3.52 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.60 m
- Lanes width: 7.40 m
- Road width: 27.40 m
- Shoulder width: 0.00 m
- Buffer width: 2.11 m
- Buffer: on-street parking
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 3
- Restrooms number: 1
- Bus stop number: 1
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: yes
- Interferences: medium

Sidewalk # 12 (Av. Americas between Carrera 58 and 56)

- 

Facade separation distance: 22.72 m
- Sidewalk length: 136.5 m
- Discontinuities length: 37.70 m
- Driveways length: 4.1 m
- Transparencies length: 87.35 m
- Roof length: 11.70 m

- Sidewalk width: 5.88 m
- Bicycle infrastructure width: 2.00 m
- Exterior lane width: 3.40 m
- Lanes width: 17.60 m
- Road width: 80.40 m
- Shoulder width: 0.22 m
- Buffer width: 3.52 m
- Buffer: on-street parking
- Speed limit: 60 km/h
- Trees number: 5
- Lanes number: 5
- Conflicts number: 1
- Restrooms number: 0
- Bus stop number: 1
- Ramps number: 2
- Bicycle infrastructure presence: yes
- Median street presence: yes
- Potholes presence: no
- Interferences: no

Sidewalk # 13 (Carrera 92 between calle 146B and 146C)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 41.1 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 0.00 m
- Roof length: 27.00 m

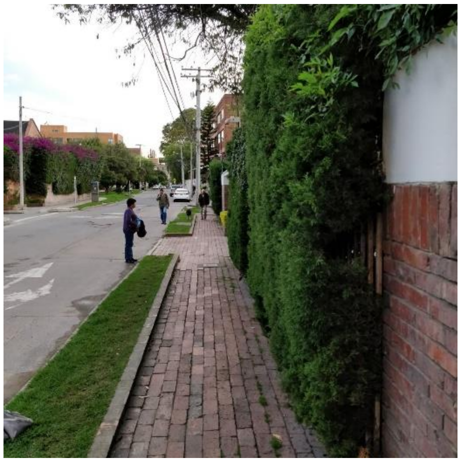
- Sidewalk width: 3.01 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 2.75 m
- Lanes width: 5.50 m
- Road width: 5.63 m
- Shoulder width: 0.13 m
- Buffer width: 1.36 m
- Buffer: no elements
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 0
- Restrooms number: 1
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: no
- Interferences: high

Sidewalk # 14 (NQS between Carrera 10 and 11)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 111.7 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 0.00 m
- Roof length: 32.07 m

- Sidewalk width: 3.88 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.25 m
- Lanes width: 13.25 m
- Road width: 46.10 m
- Shoulder width: 0.10 m
- Buffer width: 2.14 m
- Buffer: elements
- Speed limit: 60 km/h
- Trees number: 10
- Lanes number: 4
- Conflicts number: 0
- Restrooms number: 1
- Bus stop number: 1
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: no
- Interferences: low

Sidewalk # 15 (Carrera 13 with calle 136)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 38.9 m
- Discontinuities length: 15.10 m
- Driveways length: 5.3 m
- Transparencies length: 6.20 m
- Roof length: 0.00 m

- Sidewalk width: 1.33 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.80 m
- Lanes width: 7.60 m
- Road width: 7.60 m
- Shoulder width: 0.00 m
- Buffer width: 1.06 m
- Buffer: no elements
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 1
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: yes
- Interferences: no

Sidewalk # 16 (Av. cali between calle 131 and 130D bis)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 54.5 m
- Discontinuities length: 4.70 m
- Driveways length: 15.2 m
- Transparencies length: 4.70 m
- Roof length: 42.30 m

- Sidewalk width: 3.36 m
- Bicycle infrastructure width: 2.81 m
- Exterior lane width: 3.20 m
- Lanes width: 9.90 m
- Road width: 23.30 m
- Shoulder width: 0.24 m
- Buffer width: 4.08 m
- Buffer: elements
- Speed limit: 60 km/h
- Trees number: 3
- Lanes number: 3
- Conflicts number: 3
- Restrooms number: 1
- Bus stop number: 0
- Ramps number: 1
- Bicycle infrastructure presence: yes
- Median street presence: yes
- Potholes presence: no
- Interferences: high

Sidewalk # 17 (Calle 146C between Carrera 91 and 92)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 59.0 m
- Discontinuities length: 4.30 m
- Driveways length: 3.8 m
- Transparencies length: 0.00 m
- Roof length: 36.80 m

- Sidewalk width: 1.34 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 4.50 m
- Lanes width: 4.50 m
- Road width: 4.50 m
- Shoulder width: 0.00 m
- Buffer width: 2.00 m
- Buffer: on-street parking
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 0
- Restrooms number: 4
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: no
- Interferences: medium

Sidewalk # 18 (Carrera 106 between calle 131B and 132)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 75.0 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 0.00 m
- Roof length: 75.00 m

- Sidewalk width: 3.06 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 4.30 m
- Lanes width: 4.30 m
- Road width: 8.60 m
- Shoulder width: 0.00 m
- Buffer width: 0.00 m
- Buffer: no buffer
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 2
- Bus stop number: 1
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: yes
- Interferences: low

Sidewalk # 19 (Calle 26 south between Carrera 90A and 91C)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 196.6 m
- Discontinuities length: 34.00 m
- Driveways length: 0.0 m
- Transparencies length: 122.10 m
- Roof length: 80.20 m
- Sidewalk width: 2.46 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.50 m
- Lanes width: 3.50 m
- Road width: 7.80 m
- Shoulder width: 0.22 m
- Buffer width: 3.48 m
- Buffer: elements
- Speed limit: 30 km/h
- Trees number: 30
- Lanes number: 2
- Conflicts number: 1
- Restrooms number: 0
- Bus stop number: 1
- Ramps number: 3
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: no
- Interferences: no

Sidewalk # 20 (Carrera 4 between calle 12B and 12C)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 111.1 m
- Discontinuities length: 39.00 m
- Driveways length: 8.2 m
- Transparencies length: 0.00 m
- Roof length: 85.80 m
- Sidewalk width: 1.10 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.70 m
- Lanes width: 3.70 m
- Road width: 3.70 m
- Shoulder width: 0.00 m
- Buffer width: 0.00 m
- Buffer: no buffer
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 1
- Restrooms number: 4
- Bus stop number: 0
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: yes
- Interferences: no

Sidewalk # 21 (Calle 42F south between Carrera 95 and 94A)

- 

Facade separation distance: 0.00 m
- Sidewalk length: 88.4 m
- Discontinuities length: 14.00 m
- Driveways length: 2.4 m
- Transparencies length: 14.00 m
- Roof length: 75.60 m

- Sidewalk width: 2.40 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.40 m
- Lanes width: 3.40 m
- Road width: 6.80 m
- Shoulder width: 0.00 m
- Buffer width: 0.60 m
- Buffer: no elements
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 5
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 2
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: no
- Interferences: low

Sidewalk # 22 (Carrera 71D between calle 3 south and 3)

- 
Facade separation distance: 58.73 m
- Sidewalk length: 77.2 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 77.20 m
- Roof length: 0.00 m

- Sidewalk width: 3.21 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 2.60 m
- Lanes width: 8.20 m
- Road width: 27.80 m
- Shoulder width: 0.28 m
- Buffer width: 1.80 m
- Buffer: elements
- Speed limit: 30 km/h
- Trees number: 23
- Lanes number: 3
- Conflicts number: 0
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: no
- Interferences: low

Sidewalk # 23 (Calle 150A between Carrera 103B and 104)

- 
  Facade separation distance: 3.30 m
- Sidewalk length: 163.2 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 0.00 m
- Roof length: 0.00 m

- Sidewalk width: 1.64 m
- Bicycle infrastructure width: 2.21 m
- Exterior lane width: 3.10 m
- Lanes width: 6.40 m
- Road width: 9.04 m
- Shoulder width: 0.00 m
- Buffer width: 2.62 m
- Buffer: elements
- Speed limit: 30 km/h
- Trees number: 14
- Lanes number: 2
- Conflicts number: 1
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 1
- Bicycle infrastructure presence: yes
- Median street presence: no
- Potholes presence: yes
- Interferences: medium

Sidewalk # 24 (Aut. Sur on south transportation terminal)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 62.8 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 62.80 m
- Roof length: 0.00 m

- Sidewalk width: 4.05 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.40 m
- Lanes width: 7.00 m
- Road width: 61.50 m
- Shoulder width: 0.00 m
- Buffer width: 0.92 m
- Buffer: elements
- Speed limit: 60 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 1
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: no
- Interferences: no

Sidewalk # 25 (Calle 116 with Carrera 48)

- 
  Facade separation distance: 5.78 m
- Sidewalk length: 40.1 m
- Discontinuities length: 6.10 m
- Driveways length: 0.0 m
- Transparencies length: 40.10 m
- Roof length: 40.10 m

- Sidewalk width: 1.97 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.20 m
- Lanes width: 9.10 m
- Road width: 21.10 m
- Shoulder width: 0.13 m
- Buffer width: 1.49 m
- Buffer: no elements
- Speed limit: 60 km/h
- Trees number: 6
- Lanes number: 3
- Conflicts number: 0
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: no
- Interferences: no

Sidewalk # 26 (Calle 119 between Carrera 5 and 6)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 96.2 m
- Discontinuities length: 23.20 m
- Driveways length: 9.4 m
- Transparencies length: 46.70 m
- Potholes presence: yes

- Roof length: 0.00 m
- Sidewalk width: 1.45 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.20 m
- Lanes width: 6.40 m
- Road width: 6.40 m
- Shoulder width: 0.00 m
- Buffer width: 2.50 m
- Buffer: on-street parking
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 2
- Restrooms number: 5
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Interferences: medium

Sidewalk # 27 (Av. 68 between calle 1 bis and 3)

- 
  Facade separation distance: 16.91 m
- Sidewalk length: 345.0 m
- Discontinuities length: 0.00 m
- Driveways length: 40.2 m
- Transparencies length: 345.00 m
- Roof length: 0.00 m

- Sidewalk width: 2.92 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.20 m
- Lanes width: 6.80 m
- Road width: 36.60 m
- Shoulder width: 0.28 m
- Buffer width: 0.00 m
- Buffer: no buffer
- Speed limit: 60 km/h
- Trees number: 5
- Lanes number: 2
- Conflicts number: 4
- Restrooms number: 0
- Bus stop number: 4
- Ramps number: 1
- Bicycle infrastructure presence: no
- Median street presence: yes
- Potholes presence: no
- Interferences: medium

Sidewalk # 28 (Carrera 2 between calle 10 and 11)

- 
  Facade separation distance: 0.00 m
- Sidewalk length: 76.3 m
- Discontinuities length: 11.10 m
- Driveways length: 0.0 m
- Transparencies length: 14.70 m
- Roof length: 68.60 m

- Sidewalk width: 1.16 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.00 m
- Lanes width: 3.00 m
- Road width: 3.40 m
- Shoulder width: 0.39 m
- Buffer width: 0.40 m
- Buffer: no elements
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 1
- Conflicts number: 0
- Restrooms number: 1
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Potholes presence: yes
- Interferences: no

Sidewalk # 29 (NQS between Carrera 19 and connector)

- Facade separation distance: 30.64 m
- Sidewalk length: 71.4 m
- Discontinuities length: 20.25 m
- Driveways length: 0.0 m
- Transparencies length: 71.40 m
- Roof length: 0.00 m
- Sidewalk width: 4.28 m
- Bicycle infrastructure width: 2.33 m
- Exterior lane width: 4.10 m
- Lanes width: 15.40 m
- Road width: 53.14 m
- Shoulder width: 0.13 m
- Buffer width: 4.54 m
- Buffer: elements
- Speed limit: 60 km/h
- Trees number: 7
- Lanes number: 4
- Conflicts number: 0
- Restrooms number: 0
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: yes
- Median street presence: yes
- Potholes presence: no
- Interferences: no

Sidewalk # 30 (Carrera 9 between calle 36 south and Carrera 11)

- Facade separation distance: 0.00 m
- Sidewalk length: 41.7 m
- Discontinuities length: 0.00 m
- Driveways length: 0.0 m
- Transparencies length: 0.00 m
- Potholes presence: yes
- Roof length: 41.70 m
- Sidewalk width: 2.37 m
- Bicycle infrastructure width: 0.00 m
- Exterior lane width: 3.50 m
- Lanes width: 3.50 m
- Road width: 6.80 m
- Shoulder width: 0.00 m
- Buffer width: 0.00 m
- Buffer: no buffer
- Speed limit: 30 km/h
- Trees number: 0
- Lanes number: 2
- Conflicts number: 0
- Restrooms number: 2
- Bus stop number: 0
- Ramps number: 0
- Bicycle infrastructure presence: no
- Median street presence: no
- Interferences: high

11. Appendix B – Methodological review

The first PPSI methodologies were based on the relationships proposed by the Bureau of Public Roads (1950) for motor vehicles, where the only attributes considered were the pedestrian space, density, and flow (Fruin, 1971; Mōri & Tsukaguchi, 1987; Polus et al., 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985). However, this approximation was not only considered by the first methodologies, but can be also be found to be used in recent years (Alcaldia Mayor de Bogota D.C., 2005; S. S. Kim et al., 2014; Transportation Research Board, 2000). In addition to this approximation, there are also methodologies that mainly use objective attributes to calculate PPSI without considering subjective attributes from users (e.g., perceptions) considering the dependent variable to be discrete (Choi et al., 2016; Jensen, 2007) or continuous (Dandan et al., 2007; S. Kim et al., 2013; Landis et al., 2001; Mozer, 1994; Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007; Petritsch et al., 2006; Sahani et al., 2017; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2010, 2016). However, there are also some methodologies that support the PPSI calculations with the perceptions of experts (Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999; Macdonald et al., 2018; Marisamynathan & Lakshmi, 2016) or users (G. R. Bivina et al., 2018).

(Fruin, 1971; S. S. Kim et al., 2014; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985, 2000)

These five methodologies stratify the PLOS into six different groups from A to F, where A is the best PLOS and F the worst. They use pedestrian space and pedestrian flow to calculate the PLOS. First, the PLOS is determined for each attribute (Table 11.1, Table 11.2, and Table 11.3). Then, the worst PLOS calculated value is selected to be the sidewalk PLOS (Fruin, 1971; S. S. Kim et al., 2014; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985, 2000). In addition, one of the methodologies also considers the v/c ratio which defines the volume to capacity ratio where capacity is assumed to be 75 ped/min/m (Transportation Research Board, 2000).

Table 11.1. PLOS based on pedestrian space (Fruin, 1971; S. S. Kim et al., 2014; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985, 2000)

	Pedestrian Space [m^2/ped]				
PLOS	**Fruin**	**Tanaboriboon & Guyano**	**Kim et al**	**HCM 1985**	**HCM 2000**
A	> 3.25	> 2.38	> 3.30	> 3.20	> 5.60
B	2.32 – 3.25	1.60 – 2.38	2.00 – 3.30	2.30 – 3.20	3.70 – 5.60
C	1.39 – 2.32	0.98 – 1.60	1.40 – 2.00	1.40 – 2.30	2.20 – 3.70
D	0.93 – 1.39	0.65 – 0.98	0.90 – 1.40	0.90 – 1.40	1.40 – 2.20
E	0.46 – 0.93	0.37 – 0.65	0.38 – 0.90	0.50 – 0.90	0.75 – 1.40
F	< 0.46	< 0.37	< 0.38	< 0.50	< 0.75

Table 11.2. PLOS based on pedestrian Flow (Fruin, 1971; S. S. Kim et al., 2014; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985, 2000)

	Pedestrian Flow [ped/min/m]				
PLOS	**Fruin**	**Tanaboriboon & Guyano**	**Kim et al**	**HCM 1985**	**HCM 2000**
A	< 23	< 28	< 20	< 23	< 16
B	23 – 33	28 – 40	20 – 32	23 – 33	16 – 23
C	33 - 49	40 – 61	32 – 46	33 – 49	23 – 33
D	49 – 66	61 – 81	46 – 70	49 – 66	33 – 49
E	66 – 82	81 – 101	70 – 106	66 – 82	49 – 75
F	> 82	> 101	> 106	> 82	> 75

Table 11.3. PLOS based on volume to capacity ratio (Transportation Research Board, 2000)

PLOS	v/c ratio
A	< 0.21
B	0.21 – 0.31
C	0.31 – 0.44
D	0.44 – 0.65
E	0.65 – 1.00
F	> 1.00

(Polus et al., 1983)

This methodology stratifies the PLOS into four different groups from A to D, where A is the best PLOS and D the worst. However, group C is divided into two groups depending on the sidewalk use. Sidewalks that are planned to be used around high-rise office buildings are considered as C_1, and those for sport centers or central transit stations are considered as C_2. In any case, to calculate PLOS using this methodology it is necessary to determine the PLOS for each attribute first (Table 11.4). Then, the worst calculated PLOS value calculated to be the worst is selected as the sidewalk PLOS (Polus et al., 1983).

Table 11.4. PLOS based on pedestrian spaces and flow (Polus et al., 1983)

PLOS	Pedestrian Space [m^2/ped]	Pedestrian Flow [ped/min/m]
A	> 1.67	< 40
B	1.33 – 1.66	40 – 50
C_1	0.80 – 1.33	50 – 75
C_2	0.50 – 0.80	75 – 95
D	< 0.50	> 95

(Mōri & Tsukaguchi, 1987)

This methodology also stratifies the PLOS into four different groups from A to D, where A is the best PLOS and D the worst. However, it is important to note that the methodology considers three different groups of PLOS for each attribute, depending on the sidewalk width. To calculate PLOS using this methodology it is necessary to determine the PLOS for each attribute first (Table 11.5). Then, the worst calculated PLOS value is selected as the sidewalk PLOS (Mōri & Tsukaguchi, 1987).

Table 11.5. PLOS based on pedestrian density and flow (Mōri & Tsukaguchi, 1987)

PLOS	Pedestrian Density [ped/m²]			Pedestrian Flow [ped/min/m]		
A	< 0.2	< 0.2	< 0.2	< 17	< 17	< 17
B	0.2 – 0.3	0.2 – 0.5	0.2 – 0.8	17 - 41	17 - 63	17 - 76
C	0.3 – 1.5	0.5 – 1.5	0.8 – 1.5	41 - 105	63 - 105	76 - 105
D	> 1.5	> 1.5	> 1.5	> 105	> 105	> 105
Sidewalk width [m]	< 2.5	2.5 – 3.5	> 3.5	< 2.5	2.5 – 3.5	> 3.5

(Mozer, 1994)

This methodology stratifies the PLOS into five different groups from A to E, where A is the best PLOS and E the worst. This methodology was the first to introduce the term "stress" to understand the PLOS. The stress level contributes to the inference of the PLOS by considering the stress that pedestrians may feel when using a sidewalk by means of four attributes: walkarea width-volume (wwv), walkarea-outside lane buffer factor (lbf), outside lane volume, and outside lane speed. Additionally, the heavy goods vehicle factor (HGV) is used to penalize the stress level (Mozer, 1994).

The calculation of the PLOS is a six-step methodology. First step is to calculate the wwv using Equation (18). The second step is to calculate the lbf using Equation (19). The third step is to determine the peak hour volume per lane (vpl). The fourth step is to measure the speed of motor vehicles adjacent to the sidewalk. Once all attributes are calculated, the stress level for each attribute must be obtained (Table 11.6).The fifth step is to determine the heavy goods vehicle factor (HGV) as a decimal. Finally, the PLOS can be determined using Equation (20) to calculate the resultant stress level, which is then matched with the corresponding PLOS using Table 11.6 (Mozer, 1994).

$$wwv = \frac{PHV * (1 + NPM)}{\frac{WWA}{TP * FD}} \tag{18}$$

where

PHV = peak hour pedestrian volume in all directions
NPM = split of none pedestrian mode
WWA = width of the walkarea [m]
TP = travel pattern factor; oneway (1), bi-directional (2)
FD = facility design factor; if it meets Americans with Disabilities Act requirements (1); if not (5)

$$lbf = WBW * EQ \tag{19}$$

where

WBW = walkarea-outside lane buffer width [m]
EQ = aesthetic quality; if living material (1), if not (2)

Table 11.6. Attribute's stress level and PLOS (Mozer, 1994)

Stress Level	wwv	lbf [m]	vpl [veh/h/lane]	Speed [km/h]	PLOS
1	100	1.7	< 50	16	A
2	200	1.3	150	32	B
3	300	1.0	300	48	C
4	400	0.6	500	64	D
5	500	0.3	> 750	80	E

$$stress\ level = \frac{(2 * swwv) + slbf + svpl + sspeed}{5} + HGV \tag{20}$$

where

wwv = stress level from walk area width-volume
lbf = stress level from walk area-outside lane buffer width
vpl = stress level from peak hour volume per lane
speed = stress level from motor vehicle speed
HGV = heavy vehicle factor as a decimal

(Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999)

These methodologies stratify the PLOS into six different groups from A to F, where A is the best PLOS and F the worst. These methodologies introduced the use of expert perceptions of sidewalk attributes as a tool to determine the PLOS. To calculate the PLOS using Jaskiewicz's (1999) methodology, it is necessary to evaluate nine different attributes on the sidewalk (enclosure, complexity of spaces, building articulation, overhangs, path network's complexity, buffer, shade trees, transparencies, and physical condition) from 1 to 5 (5 = excellent, 4 = good, 3 = average, 2 = poor, 1 = very poor). Then, the scores obtained must be aggregated and averaged to calculate the overall sidewalk evaluation and using Table 11.7 the PLOS can be obtained. Similarly, for the methodology developed by Gallin (2001) it is necessary to evaluate eleven different weighted attributes (access = 5, path width = 4, surface quality = 5, crossing opportunities = 4, support facilities = 2, connectivity = 4, path environment = 2, potential for vehicle conflict = 3, path user volume = 3, mix of path users = 4, and personal security = 4) from 0 to 4 as is outlined in Table 11.8. Then, the weight of each attribute is multiplied by the evaluation obtained from 0 to 4. Finally, the weighted scores obtained for each attribute must be aggregated and using Table 11.6 the PLOS can be obtained. To calculate PLOS using (Christopoulou & Pitsiava-Latinopoulou's (2012) methodology it is necessary to evaluate eighteen different weighted attributes (buffer width = 1.8, traffic speed = 1.2, buffer type elements = 1.5, traffic noise = 0.3, traffic volume = 0.9, discontinuities = 0.6, sidewalk width = 2.4, sidewalk width without obstacles = 1.2, guides for the blind = 0.8, pavement condition = 2, ramps = 1.6, trees and plants = 0.4, pedestrian volume = 1.8, safety sense = 0.3, maneuvers to avoid obstacles = 1.5, maneuvers to avoid vertical obstacles = 1.2, queue formation = 0.9, multimodal transport presence = 0.6) from 0 to 2 as laid out in Table 11.9. Then, the weight of each attribute is multiplied by the evaluation obtained from 0 to 2. Finally, the weighted scores obtained for each attribute must be aggregated and the PLOS can be obtained using Table 11.7.

Table 11.7. PLOS based on sidewalk attributes and perceptions (Gallin, 2001; Jaskiewicz, 1999)

PLOS	Jaskiewicz	Gallin	Christopoulou & Pitsiava-Latinopoulou
A	4.0 – 5.0	> 132	> 35
B	3.4 – 3.9	101 – 131	28 – 35
C	2.8 – 3.3	69 – 100	21 – 28
D	2.2 – 2.7	37 – 68	14 – 21
E	1.6 – 2.1	< 36	7 – 14
F	1.0 – 1.5	< 15 for access	< 7

Table 11.8. PLOS assessment (Gallin, 2001)

Attribute	0	1	2	3	4
Access	Problems for general users	Items inappropriate for people with disabilities	Major problems for people with disabilities	Minor problems for people with disabilities	Full access for people with disabilities
Path width	No pedestrian path	0 – 1 [m]	1.1 – 1.5 [m]	1.6 – 2 [m]	> 2 [m]
Surface quality	Very poor quality	Poor quality	Moderate quality	Reasonable quality	Excellent quality
Crossing opportunities	None provided	Some provided but poorly located	Some provided and reasonably well located	Adequate crossing facilities	Dedicated pedestrian crossing facilities
Support facilities	Non-existent	Few provided and poorly located	Few provided and reasonably well located	Several provided	Many provided
Connectivity	Non-existent	Poor	Reasonable	Good	Excellent
Path environment	No kerb	Kerb 0 – 1 [m]	Kerb 1 – 2 [m]	Kerb 2 – 3 [m]	Kerb > 3 [m]
Potential for vehicle conflict	> 25 per km	16 – 25 per km	10 – 15 per km	1 – 10 per km	0
Path user volume	> 350 per day	226 – 350 per day	151 – 225 per day	81 – 150 per day	< 80 per day
Mix of path users	On wheels > 70%	On wheels 51% - 70%	On wheels 21% - 50%	On wheels 5% - 20%	On wheels < 5%
Personal security	Unsafe	Poor	Reasonable	Good	Excellent

Table 11.9 PLOS attribute scores for Christopoulou & Pitsiava-Latinopoulou (2012)

Attributes	Score 0	1	2
Buffer width	Confined to shoulder	< width of an automobile	> width of an automobile
Traffic speed	> 60 km/h	30 – 60 km/h	< 30 km/h
Buffer type elements	none	Linear with cross	Linear without crossing opportunities
Traffic noise	loud	tolerable	imperceptible
Traffic volume	congestion	Continuous flow	Easy change of lane
Discontinuities	> 1/100 m	1/100 m – 1/200 m	< 1/200 m
Sidewalk width	< 1.5 m	1.5 – 2.20 m	> 2.20 m
Sidewalk width without obstacles	< 1.8 m	1.8 – 2.20 m	> 2.20 m
Blind's guides	Does not exist	Exists with variations from specifications	Exists according to specifications
Pavement condition	Bad condition	Medium condition	Good condition
Ramps	Do not exist	Exists with variations from specifications	Exists according to specifications
Trees and plants	Do not exist	Existence decreasing free width below 1.5m	Existence and does not cause problems
Pedestrian volume	heavy	moderate	Easy movements
Safety sense	inadequate	Lighting with frequent dark spots	Adequate lighting
Maneuvers to avoid obstacles	frequent	moderate	Rare
Maneuvers to avoid vertical obstacles	frequent	moderate	Rare
Queue formation	frequent	moderate	Rare
Multimodal transport presence	Infrastructure does not exist	Limited infrastructure	Important infrastructure

(Alcaldia Mayor de Bogota D.C., 2005)

This methodology was developed to update a methodology from 1998 and was mainly based on the 2000 version of the Highway Capacity Manual methodology. The most relevant concepts from the Highway Capacity Manual were considered and adapted to the city of Bogotá. This methodology stratifies the PLOS into six different groups from A to F, where A is the best PLOS and F the worst. It uses pedestrian space, flow, and the flow-capacity ratio, considering the capacity to be 75 ped/min/m. A two-step process calculates the PLOS. First, the PLOS is determined for each attribute (Table 11.10). Then, the worst calculated PLOS value is selected as the sidewalk PLOS.

Table 11.10. PLOS based on Alcaldia Mayor de Bogota D.C. (2005)

PLOS	Space [m^2/ped]	Flow [ped/m/min]	V/C
A	> 7.00	< 14	< 0.049
B	1.00 – 7.00	15 – 91	0.050 – 0.317
C	0.77 – 0.99	92 – 115	0.318 – 0.401
D	0.40 – 0.76	116 – 194	0.402 – 0.676
E	0.17 – 0.39	195 – 287	0.677 – 1.000
F	< 0.17	> 287	> 1.000

(Landis et al., 2001; Sahani et al., 2017; State of Florida Department of Transportation, 2009)

These methodologies stratify the PLOS into six different groups from A to F, where A is the best PLOS and F the worst. One of these methodologies was the first to propose a model obtained from users' perceptions but that used only sidewalk attributes to calculate the PLOS (Landis et al., 2001). Additionally, this methodology inspired others to use the same concept to develop a PLOS calculation model (Sahani et al., 2017; State of Florida Department of Transportation, 2009). The calculation of PLOS using the above-mentioned methodologies is a 2-step procedure. The first step is to calculate the model score using Equation (21) for Landis et al. (2001), Equation (21) for State of Florida Department of Transportation (2009), and Equations (23) to (25) for Sahani et al. (2017). Then, the PLOS can be obtained using Table 11.11 and the previously-calculated model score.

$$PLOS\ score = -1.2021 \ln(W_{ol} + W_l + f_p * \%OSP + f_b * W_b + f_{sw} * W_s) + 0.253 \ln\left(\frac{Vol_{15}}{L}\right) + 0.0005 * SPD^2 + 5.3876 \quad (21)$$

$$PLOS\ score = -1.2276 \ln(W_{ol} + W_l + f_p * \%OSP + f_b * W_b + f_{sw} * W_s) + 0.0091 \left(\frac{Vol_{15}}{L}\right) + 0.004 * SPD^2 + 6.0468 \quad (22)$$

where

W_{ol} = width of outside lane [ft]
W_l = width of shoulder or bike lane [ft]
f_p = on-street parking effect coefficient (0.20)
%OSP = percentage of segment with on-street parking
f_b = buffer area barrier coefficient (5.37 for trees)
W_b = buffer width [ft]
f_{sw} = sidewalk presence coefficient (6 – 0.3W_s)
W_s = sidewalk width [ft]
Vol_{15} = average traffic during a 15 minute period
L = total number of road lanes
SPD = motor vehicle's average running speed [mph]

$$PLOS\ score = 0.808 - 1.25 \ln F_{ws} + 0.267 \ln F_{mv} + 0.0059 F_{nmv} + 0.035 F_{ped} + 0.384 e^{0.401 F_{ob}} + 0.033 S_p \quad (23)$$

with

$$F_{ws} = W_{ls} + W_{ln} + W_b + W_s \tag{24}$$

$$F_{ob} = Ob_v + Ob_l + \%VE + \%OSP \tag{25}$$

where

F_{ws} = factor for width separation
W_{ls} = lateral separation width [m]
W_{ln} = non-motorized vehicle lane width [m]
W_b = buffer width [m]
W_s = sidewalk width [m]
F_{mv} = motorized vehicle volume [PCU/lane/15 min]
F_{nmv} = non-motorized vehicle volume [15 min]
F_{ped} = pedestrian volume [15 min]
F_{ob} = factor of total obstruction
Ob_v = number of walking barriers or visual obstructions
Ob_l = number of live stocks [15 min]
%VE = percentage of public vendor space
%OSP = percentage of segment with on-street parking
S_p = vehicle average speed [km/h]

Table 11.11. PLOS based on model score (Landis et al., 2001; Sahani et al., 2017; State of Florida Department of Transportation, 2009)

PLOS	Landis et al.	FDOT	Sahani et al.
A	< 1.5	< 1.5	< 1.8
B	1.5 – 2.5	1.5 – 2.5	1.8 – 2.6
C	2.5 – 3.5	2.5 – 3.5	2.6 – 3.4
D	3.5 – 4.5	3.5 – 4.5	3.4 – 4.2
E	4.5 – 5.5	4.5 – 5.5	4.2 – 5.1
F	> 5.5	> 5.5	> 5.1

(Dandan et al., 2007; S. Kim et al., 2013; Marisamynathan & Lakshmi, 2016; Petritsch et al., 2006)

These methodologies stratify the PLOS into six different groups from A to F, where A is the best PLOS and F the worst. One calculates the PLOS by looking at potential conflicts along the sidewalk for pedestrians and the effects of vehicles on pedestrians (Petritsch et al., 2006). Another focuses on the potential positive and negative effects that motor vehicles and active transportation modes including pedestrians may cause (Dandan et al., 2007). The third considers attributes from the pedestrian infrastructure and from the vehicle infrastructure adjacent to pedestrians (S. Kim et al., 2013). Finally, the last considers sidewalk attributes and pedestrians' road safety to calculate the PLOS (Marisamynathan & Lakshmi, 2016). In these cases, to calculate the PLOS it is necessary to follow a 2-step procedure. The first step is to calculate the model score using Equation (26) for Petritsch et al., (2006), Equation (27) for Dandan et al (2007), Equation (28) for S.

Kim et al. (2013), and Equation (29) for Marisamynathan & Lakshmi (2016). Then, the PLOS can be obtained using Table 11.12 and the previously-calculated model score.

$$PLOS\ score = 0.001 * \left(\frac{Xing\ width}{mile}\right) + 0.008 * (Vol_{15}) + 1.43 \quad (26)$$

where

Xing width/mile	= total width of crossings at conflict locations per mile [ft]
Vol_{15}	= average 15-min volume on adjacent roadway

$$PLOS\ score = -1.43 + 0.006Q_B - 0.003Q_P + 0.056\left(\frac{Q_V}{W_r}\right) + 11.24(P - 1.17P^3) \quad (27)$$

where

Q_B	= bicycle traffic during a five-minute period
Q_P	= pedestrian traffic during a five-minute period
Q_V	= vehicle traffic during a five-minute period [pcu]
P	= driveway access quantity per meter
W_r	= distance between sidewalk and vehicle lane [m]

$$PS = 2.485 + 3.001 \ln W_t - 1.438 \ln W_b - 0.544 \ln W_s + 0.045SPD + 0.017VOL_5 \quad (28)$$

where

PS	= LOS perceived by pedestrians
W_t	= traffic lane width [m]
W_b	= buffer width [m]
W_s	= sidewalk width [m]
SPD	= vehicle speed [km/h]
VOL_5	= vehicle volume [5 min]

$$PLOS = 3.404 \ln(SSC + G_{sw} + B_{sw}) + 15.215 \ln(Vol_{15}) - 17.639 \ln(W_{sw}) - 20.770 \quad (29)$$

where

SSC	= sidewalk surface condition (1: very good, 2: good, 3: average, 4: poor, 5: very poor)
G_{sw}	= guard rail presence (0: absence, 1: presence)
B_{sw}	= barrier presence (0: absence, 1: presence of trees/pole/boxes/drainage, 2: combination)
Vol_{15}	= traffic volume [15 min]
W_{sw}	= sidewalk width [m]

Table 11.12. PLOS based on model score (Dandan et al., 2007; S. Kim et al., 2013; Marisamynathan & Lakshmi, 2016; Petritsch et al., 2006)

PLOS	Petritsch et al.	Dandan et al.	Kim et al.	Marisamynathan et al.
A	< 1.5	< 2.0	< 1.5	< 15
B	1.5 – 2.5	2.0 – 2.5	1.5 – 2.5	15 – 30
C	2.5 – 3.5	2.5 – 3.0	2.5 – 3.5	30 – 45
D	3.5 – 4.5	3.0 – 3.5	3.5 – 4.5	45 – 60
E	4.5 – 5.5	3.5 – 4.0	4.5 – 5.5	60 – 85
F	> 5.5	> 4.0	> 5.5	> 85

(Muraleetharan et al., 2005; Muraleetharan & Hagiwara, 2007)

These methodologies propose that four different sidewalk attributes (width and separation, obstructions, flow rate, and bicycle events) improve the utility of pedestrians when walking. In addition, these methodologies establish that there is a lineal relation between the calculated utility and the overall LOS score. In general, to calculate the overall LOS score it is necessary to obtain the individual utility for each sidewalk attribute using Table 11.13 first. Then, with this information the total utility can be calculated using Equation (30) for Muraleetharan et al. (2005) and Equation (31) for Muraleetharan & Hagiwara (2007). Finally, to calculate the overall LOS score Equation (32) can be used for Muraleetharan et al. (2005) which is rated between 0 to 10, and Equation (33) for Muraleetharan & Hagiwara (2007) which is rated from 0 to 6.

Table 11.13. Utilities based on sidewalk attributes

Attribute	Level	Utility
Width and separation	1. More than 3 m wide and excellent separation	1.36
	2. From 1.5 to 3 m and reasonable separation	0.15
	3. Less than 1.5 m wide and no separation	-1.52
Obstructions	1. No obstructions	0.75
	2. From 1 to 5 obstructions per 100 m	0.02
	3. More than 5 obstructions per 100m	-0.77
Flow rate [ped/min/m]	1. Less than 24	1.53
	2. From 24 to 49	0.04
	3. More than 49	-1.57
Bicycle events	1. < 61 events/h	1.72
	2. From 61 to 144 events/h	-0.58
	3. > 144 events/h	-1.14

$$Total\ utility\ (TU) = 3.90 + \sum_{i=1}^{4} u_i \quad (30)$$

$$Total\ utility\ (TU) = \sum_{i=1}^{4} u_i \quad (31)$$

$$Overall\ LOS\ score = \begin{cases} TU < 3.53 & 5 * \left(\frac{TU + 1.1}{4.63}\right) \\ TU > 3.53 & 5 + \left(5 * \left(\frac{TU - 3.53}{5.73}\right)\right) \end{cases} \quad (32)$$

$$Overall\ LOS\ score = 6 * \left(\frac{TU + 5}{10.36}\right) \quad (33)$$

(Choi et al., 2016; Jensen, 2007)

These methodologies proposed a discrete Likert scale for satisfaction to predict PLOS. Jensen (2007) was one of the first authors to propose a discrete scale with six different categories (very satisfied (VS), moderately satisfied (MS), a little satisfied (LS), a little dissatisfied (LD), moderately dissatisfied (MD), and very dissatisfied (VD)) to calculate PLOS. Almost ten years later, Choi et al. (2016) also propose a discrete scale to predict PLOS using satisfaction, but only considering three different categories (satisfied, average, and unsatisfied). A logit model was proposed to predict the PLOS in both cases where a utility is calculated to predict the probability to be selected for each of the satisfaction categories considering some attributes of the sidewalk.

Jensen (2007) states that to calculate the PLOS it is necessary to obtain the cumulative utility for each category considering some sidewalk attributes using Equation (34). To use Equation (34), the discrete attribute parameters can be obtained using Table 11.14. Once the utility cumulative is calculated, the probability for each satisfaction category can be obtained using Equations (35) to (40). The satisfaction category with the highest probability will be selected as the PLOS for the sidewalk.

$$\begin{aligned} logit(p) = {} & \alpha + WA + AREA - 0.002476 * MOT + 0.0000003364 * MOT^2 \\ & - 0.0303 * SPEED + 0.00002211 * SPEED * MOT - 0.005432 \\ & * PED + 0.000005062 * PED^2 - 0.003772 * BIKE + 0.000003111 \\ & * BIKE^2 + 0.4408 * BUF - 0.0365 * BUF^2 - 0.05286 * PARK \\ & + 1.0180 * MED + 0.2938 * SB + 0.6277 * BL + 0.7380 * LANE \\ & + 0.3311 * TREE \end{aligned} \quad (34)$$

where

logit(p)	= utility function cumulative logit model
α	= parameter of the response level of satisfaction (Table 11.14)
WA	= type of walking area (Table 11.14)
AREA	= type of roadside development or landscape (Table 11.14)
MOT	= motor vehicles per hour
SPEED	= average motor vehicle speed [km/h]
PED	= number of pedestrians per hour
BIKE	= number of bicycles and mopeds per hour
BUF	= width of buffer area [m]
PARK	= parked motor vehicle on road per 100 m
MED	= 1 if median present, 0 otherwise
SB	= sidewalk width [m]
BL	= sidewalk and nearest drive lane width [m]

LANE = 1 if there are four or more drive lanes, 0 otherwise
TREE = 1 if there is one tree or more per 50 m, 0 otherwise

Table 11.14. Discrete attribute parameters (Jensen, 2007)

α		WA		AREA	
Very satisfied	-2.8526	Sidewalk concrete	3.5486	Residential	0.4871
Moderately satisfied	-1.2477	Sidewalk asphalt	1.9149	Shopping	0.5385
A little satisfied	-0.0646	Bicycle track	1.0124	Mixed	-1.6349
A little dissatisfied	0.8758	Bike lane	-2.8293	Rural fields	1.2380
Moderately dissatisfied	2.2543	Driving lane	-3.6464	Rural forest	0.5122

$$VS = 1 - \frac{1}{1 + \exp(logit(p)_{VS})} \quad (35)$$

$$MS = 1 - VS - \frac{1}{1 + \exp(logit(p)_{MS})} \quad (36)$$

$$LS = 1 - VS - MS - \frac{1}{1 + \exp(logit(p)_{LS})} \quad (37)$$

$$LD = 1 - VS - MS - LS - \frac{1}{1 + \exp(logit(p)_{LD})} \quad (38)$$

$$MD = 1 - VS - MS - LS - LD - \frac{1}{1 + \exp(logit(p)_{MD})} \quad (39)$$

$$VD = 1 - VS - MS - LS - LD - MD \quad (40)$$

Similarly, for the methodology proposed by Choi et al. (2016) it is necessary to obtain the cumulative utility for each category including some sidewalk attributes using Equation (41). Once the utility cumulative is calculated, the probability for each satisfaction category can be obtained using Equations (42) to (44). The satisfaction category with the highest probability is selected as the PLOS for the sidewalk.

$$logit(p) = \beta - 0.216X_1 - 0.093X_2 - 0.260X_3 + 0.027X_4 + 0.061X_5 - 0.293X_6 - 0.332X_7 - 0.137X_8 + 0.317X_9 + 0.060X_{10} \quad (41)$$

where

logit(p) = utility function cumulative logit model
β = satisfaction parameter (satisfied = -0.574, average = 3.184)
X_1 = pedestrian volume per day
X_2 = crosswalk presence (1 = yes, 0 = no)
X_3 = number of lanes per direction
X_4 = median presence (1 = yes, 0 = no)
X_5 = bike lane presence (1 = yes, 0 = no)
X_6 = driveway presence (1 = yes, 0 = no)
X_7 = planting strip presence (1 = yes, 0 = no)
X_8 = bus stop presence (1 = yes, 0 = no)
X_9 = commercial land use (1 = yes, 0 = no)
X_{10} = business land use (1 = yes, 0 = no)

$$Satisfied = 1 - \frac{1}{1 + \exp\left(logit(p)_{Satisfied}\right)} \quad (42)$$

$$Average = 1 - Satisfied - \frac{1}{1 + \exp\left(logit(p)_{Average}\right)} \quad (43)$$

$$Unsatisfied = 1 - Satisfied - Average \quad (44)$$

(Transportation Research Board, 2010, 2016)

These methodologies stratify the PLOS into six different groups from A to F, where A is the best PLOS and F the worst. These methodologies were inspired by those proposed previously that use pedestrian perceptions about sidewalk characteristics to calculate PLOS. Both methodologies use a similar procedure to calculate PLOS. In both cases, the PLOS score needs to be calculated first with Equation (45) and using Equations (46) to (48). Then, using Table 11.16 and pedestrian space for Transportation Research Board (2010) or Table 11.17 for Transportation Research Board (2016) and from the previously-calculated model score the PLOS can be obtained.

$$PLOS\ score = 6.0468 + F_w + F_v + F_s \quad (45)$$

with

$$F_w = -1.2276 \ln(W_v + 0.5W_l + 50p_{pk} + W_{buf} f_b + W_{aA} f_{sw}) \quad (46)$$

$$F_v = 0.0091 \frac{v_m}{4N_{th}} \quad (47)$$

$$F_s = 4\left(\frac{S_R}{100}\right)^2 \quad (48)$$

where

W_v = effective total width of outside through lane, bicycle lane, and shoulder
W_l = total width of shoulder, bicycle lane, and parking lane
p_{pk} = proportion of on-street parking occupied [decimal]
W_{buf} = buffer width [ft]
f_b = buffer area barrier coefficient (5.37 for trees, otherwise 1.00)
W_{aA} = adjusted available sidewalk width = min (W_A, 10) [ft]
W_A = available sidewalk width (W_T – W_{buf}) [ft]
W_T = total walkway width [ft]
f_{sw} = sidewalk width coefficient (6 – 0.3W_{aA})
v_m = midsegment demand flow rate [veh/h]
N_{th} = number of through lanes on the segment
S_R = motorized vehicle running speed [mi/h]

where

Table 11.15. Conditions for PLOS score (Transportation Research Board, 2010, 2016)

Condition	Condition is satisfied	Condition is not satisfied
$v_m > 160$ veh/h or $W_A > 0$ ft	$W_v = W_{ol}+W_{bl}+W_{os}+W_{pk}$	$W_v = (W_{ol}+W_{bl}+W_{os}+W_{pk})(2–0.005v_m)$
$p_{pk} > 0.25$ or $W_{bl}+W_{os}+W_{pk} < 10$	$W_l = W_{bl}+W_{os}+W_{pk}$	$W_l = 10$

W_{ol} = width of outside through lane [ft]
W_{os} = adjusted width of paved shoulder (if curb present $W_{os} = W_{os}^* - 1.5 > 0$, otherwise $W_{os} = W_{os}^*$ [ft]
W_{os}^* = width of paved outside shoulder [ft]
W_{bl} = width of the bicycle lane [ft]
W_{pk} = width of striped parking lane [ft]

Table 11.16. PLOS based on model score and pedestrian space

PLOS score	Pedestrian space [ft²/ped]					
	> 60	40 – 60	24 – 40	15 – 24	8 – 15	< 8
< 2.00	A	B	C	D	E	F
2.00 – 2.75	B	B	C	D	E	F
2.75 – 3.50	C	C	C	D	E	F
3.50 – 4.25	D	D	D	D	E	F
4.25 – 5.00	E	E	E	E	E	F
> 5.00	F	F	F	F	F	F

Table 11.17. PLOS based on last HCM model score

PLOS score	PLOS
< 1.50	A
1.50 – 2.50	B
2.50 – 3.50	C
3.50 – 4.50	D
4.50 – 5.50	E
> 5.50	F

(G. R. Bivina et al., 2018; Macdonald et al., 2018; Talavera-Garcia & Soria-Lara, 2015)

Two of these methodologies stratify the PPSI into categorical groups from A to F, where A is the best rated indicator and F the worst. Both Macdonald et al. (2018) and Talavera-Garcia & Soria-Lara (2015) base their PPSI calculation on physical sidewalk attributes and the infrastructure around the sidewalk. In the case of Macdonald et al. (2018), the output is the quality-of-service (QoS), and with Talavera-Garcia & Soria-Lara (2015), the output is the Quality of Pedestrian Level of Service (Q-PLOS). In addition, G. R. Bivina et al. (2018) proposed one of the first methodologies that needs pedestrians' perceptions of some sidewalk attributes to calculate the PLOS.

There is a two-step process to calculate the Q-PLOS using Talavera-Garcia & Soria-Lara's (2015) methodology. The first step is to calculate the Q-PLOS score using Equation (49) and Table 11.18. Then, the Q-PLOS can be obtained using Table 11.20 and the previously-calculated Q-PLOS score.

$$QPLOS = \frac{0.76 * C + 0.95 * W + 0.91 * S + 0.98 * TD + 0.87 * CD}{4.47} \quad (49)$$

where

Table 11.18. Sidewalk attribute parameters (Talavera-Garcia & Soria-Lara, 2015)

QL	Connectivity (C)	Width [m] (W)	Speed [km/h] and lanes (S)	Trees density [tree/km^2] (TD)	Commercial density [shops/km^2] (CD)
1	According to city's values	> 3		> 20000	According to city's values
2		2.25 – 3	20 – 30	15000 – 20000	
3		1.5 – 2.25	50 (1 lane)	10000 – 15000	
4		0.9 – 1.5	50 (2 lanes)	5000 – 10000	
5		< 0.9	50 (3 lanes)	< 5000	

Similarly, a two-step process is necessary for that proposed by G. R. Bivina et al. (2018). The first step is to calculate the PLOS score using Equation (50) and Table 11.19. Then, the PLOS can be obtained by using Table 11.20 and the previously-calculated PLOS score.

$$PLOS = \sum_{i=1}^{10} A_i * B_i \quad (50)$$

where

A_i = relative importance weight of each sidewalk characteristic ()
B_i = Perceived satisfaction score for each sidewalk characteristic (from 1 to 5)

Table 11.19. Sidewalk characteristics' weights per land use (G. R. Bivina et al., 2018)

Sidewalk characteristics	Land Uses				
	Residential	Commercial	Institutional	Terminal	Recreational
Surface	3.14	3.17	3.35	2.36	2.40
Width	2.63	3.53	3.28	1.98	3.04
Obstructions	2.39	3.30	3.47	1.77	3.31
Vehicle conflict	2.71	3.04	3.51	2.15	3.30
Continuity	2.22	2.51	2.71	1.71	2.90
Encroachment	2.46	3.08	3.08	1.55	2.71
Crossing facilities	2.71	3.23	3.35	1.97	3.33
Security	2.31	2.72	2.98	1.94	2.78
Comfort	1.96	2.87	2.34	1.52	3.34
Environment	2.20	2.97	3.09	1.67	2.92

Finally, for the methodology proposed by Macdonald et al. (2018), a four-step process is applied. The first step is to calculate the block segment score according to eight different sidewalk characteristics. When each core complies with the sidewalk infrastructure, one point is added to the score. A maximum of eight points can be obtained from this step.

- Core 1: Sidewalk width (+1 if accomplish at least one)
  - Arterial street, 4 lanes or fewer: 12 feet

  - Arterial street, 5 lanes or more: 15 feet
  - Urban core commercial street, 4 lanes, up to 10 story buildings: 12 feet
  - Urban core commercial street, 4 lanes, 10 + story buildings: 15 feet
  - Collector street, 2 lanes: 8 feet
  - Neighborhood commercial, 2 lanes: 10 feet
- Core 2: Lanes and speed (+1 if accomplish)
  - Five or fewer traffic lanes
  - Vehicle speeds no more than 35 mph
- Core 3: Buffer (+1 if accomplish at least three)
  - On-street parking
  - Delineated bike lane
  - Planting strip with kerb present
  - Line of street trees planted no more than 30 ft apart
  - Line of permanent street furniture
- Core 4: Trees (+1 if accomplish)
  - Tree canopy presence
- Core 5: Visual (+1 if accomplish at least three)
  - Transparent building materials
  - Varying storefronts or facades
  - Activated sidewalk elements presence
  - Adjacent open spaces
  - Public art
  - Buildings of architectural interest
- Core 6: Enclosure (+1 if accomplish at least one)
  - Streets wider than two lanes, building height at least half the ROW width
  - Streets up to two lanes, building of any height
  - If there are open spaces, presence of features giving a sense of enclosure
- Core 7: Protected crossing (+1 if accomplish at least two)
  - Painted crosswalk
  - Pedestrian walk signals
  - Medians presence
  - Stop signs
  - Traffic circles
- Core 8: Accessibility (+1 if accomplish at least three)
  - Kerb ramps
  - Tactile warning strips
  - Audible walk signals
  - Level pavement

The second step is to bonify the block segment according to ten different assets that may be found on the sidewalk, that generate a positive effect on pedestrians (Macdonald et al., 2018). For each asset observed on the sidewalk, 0.5 is added to the segment's score. A maximum of five points can be obtained from this step.

- Attractive views of hills, mountains, water, major buildings, urban skylines or other natural or architectural landmark
- High-quality signage or other wayfinding aids such as maps and kiosks
- Connection to off-street multi-use pathways or regional trail network

- Location within a cultural or historic district, safe-routes-to-school route or other pedestrian-friendly designation
- Presence of high-quality landscape architecture within or adjacent to the right-of-way, including storm water management features
- Presence of raised crosswalks, special pavements, pedestrian scrambles or other pedestrian-friendly intersection treatments at either end of block segment
- Location on a direct path to nearby transit stop or major civic destination such as school, museum, stadium or concert hall
- Design mitigation to address adverse environmental conditions, such as excessive wind, rain, and sun exposure
- Extra traffic calming devices, such as chicanes or speed bumps
- On boulevards, walking paths along the medians

The third step is to detract points from the block segment according to nine different characteristics that potentially generate nuisances for pedestrians (Macdonald et al., 2018). For each of these features observed on the sidewalk, 0.5 is added to the segment's demerits. A maximum of 4.5 points can be obtained in this step.

- Inadequate municipal services and maintenance (at least two)
    - Lack of streetlights for the whole block length
    - Lack of at least one trash/recycling receptacle on each side of the street
    - Non-level, broken or poorly maintained pavement
    - Excessive graffiti, broken windows or other evidence of vandalism
    - Poor drainage or localized flooding
- Excessive street-level building vacancies (three or more)
- Excessively steep grade
- Poorly controlled interactions between pedestrians, bicycles, and skateboards
- Excessive noise from at least one permanent source
- Excessive visual clutter from overhead utility lines or other permanent features
- Three or more driveways
- Presence of major barriers to pedestrians
- Very poor or no design mitigations to address adverse environmental conditions

Finally, last step is to calculate the resulting final score using Equation (51) and the PLOS using Table 11.20.

$$Final\ score = block\ segment\ score + bonus - demerits \tag{51}$$

Table 11.20. PLOS thresholds (G. R. Bivina et al., 2018; Macdonald et al., 2018; Talavera-Garcia & Soria-Lara, 2015)

PLOS/Q-PLOS/SQ	Talavera-Garcia & Soria-Lara	Macdonald et al	Bivina et al
A	< 1.5	> 6.0	> 125
B	1.5 – 2.5	5.0 or 5.5	100 – 125
C	2.5 – 3.5	4.0 or 4.5	75 – 100
D	3.5 – 4.5	3.0 or 3.5	49 – 75
E	> 4.5		25 – 50
F		< 3.0	> 25