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Do attitudes and perceptions help to explain cycling infrastructure quality of service?

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A R T I C L E I N F O

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A B S T R A C T

Many approaches have been developed to assess the performance or Quality of Service (QoS) rendered by cycling infrastructure. The most common methodologies (Level of Service/Level of Traffic Stress) do not consider user inputs. In other disciplines, user perceptions constitute a powerful tool that can help improve and tailor designs. This study was intended to explore the effect of cyclists' attitudes and perceptions on the perceived QoS of different cycling infrastructures using Structural Equation Modeling (SEM). The SEM model was developed using cyclist surveys applied at 16 locations comprising all typologies of cycling infrastructure in Bogotá, Colombia. We found that user attitudes and perceptions of tangible (e.g., pavement) and intangible attributes (e.g., enjoyment) can explain cyclists' QoS. The results lead to a better understanding of typical Global South cyclist perceptions when riding, and provide an accurate tool with which to improve cycling infrastructure QoS from a cyclist perspective.

1. Introduction

Promoting bicycle use as a regular transportation mode for the general public has become a principal strategy used in cities to contribute to sustainability and to enhance the benefits it brings to society and individuals. These benefits derive from the fact that the bicycle is a zero-emissions vehicle that demands little space to operate (Haines et al., 2009), while enhancing health benefits for the individuals engaged in physical activity (Garrard et al., 2012; Oja et al., 2011; Pucher and Buehler, 2012). Cities are working towards increasing bicycle ridership on account of the overall positive benefits to individuals and society, including those detailed above (Börjesson and Eliasson, 2012; Krizek, 2007). Indeed, several case studies have shown positive results from bicycle ridership (Dill, 2009; Lanzendorf and Busch-Geertsema, 2014; Marqués et al., 2015; Pucher et al., 2010; Rosas-Satizábal and Rodriguez-Valencia, 2019) and so many cities worldwide are putting attractive, safe, and functional bicycle infrastructure on the agenda.

Level of service, satisfaction, comfort, quality of service (QoS), and level of traffic stress (LTS), are among the most frequently examined methods used to assess bicycle infrastructure service or performance. These methods have a common feature in that they

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explain the perceived infrastructure service or performance by means of objective variables. Particularly for cyclists, these measurable variables comprise geometric dimensions (e.g., widths or segregation), traffic characteristics (e.g., speed and volume), and interferences, among many others. However, these approaches do not explicitly consider the explanatory potential of users' perspectives on the overall performance or QoS of any given stretch of bicycle infrastructure.

Unlike motorists, cyclists and pedestrians experience sensory interaction with the local environment (Rodriguez-Valencia et al., 2020). Based on the environmental psychology theory, environmental stimuli produce emotions and feelings (Bell et al., 2006) which generate an emotional state that can cause approach (desire to stay) or avoid (desire to leave and not return) behavior (Mehrabian and Russell, 1974). Perception reports are required as they can help us discover how people identify this sensory information, and whether perceptions of certain attributes, situations, or environments can vary among respondents. Moreover, perceptions of travelers with respect to infrastructure may vary depending on the geographical location. This research contributes to the understanding of cycling infrastructure quality of service from a user perceptual perspective, unveiling how cyclists perceive other road actors and the built environment in a Global South context.

This paper presents a cognitive map explaining the overall QoS perceived by cyclists, based on their perceptions of the local environment (e.g., security perception), its attributes (e.g., paving perception), and personal attitudes (e.g., "I like to ride a bicycle"). The diagram structure is based on the literature and on new findings obtained from Factor Analysis techniques and Structural Equation Modeling (SEM), using data from cyclists' responses to an intercept survey conducted in Bogotá, Colombia. This study only considers users' perception and attitudinal variables when questioned on-site. Objective measures from cyclists (e.g., age) and infrastructure are not included in the analysis as it seeks to understand the phenomena which explain cyclists' QoS perceptions when riding a bicycle, based on cyclist attitudes and perceptions of the built environment alone.

Evidence provided in this paper enriches the dialogue on the use of subjective attributes to understand the variables affecting cyclists' perceptions of QoS, outlining how perceptions can be used to identify latent variables and explain QoS from the cyclists' perspective. This paper may also serve to open up new possibilities for research and design in the field of transportation. The findings regarding the relationships explaining the perception of infrastructure services from a systematic perspective can be used to try to retain and attract more cyclists in a metropolis of more than eight million inhabitants such as Bogotá.

2. Literature review

The Level of Service (LOS) concept, introduced in the Highway Capacity Manual (HCM) by the Transportation Research Board (1965) is the traditional method used to assess the performance of any transportation infrastructure. It is also one of the most popular. Data input used for calculating LOS for motorized segments include solely objective measurements (e.g., lane width, heavy traffic volume, edge clearances, free-flow speed) which were intended to capture road users' perceptions measured on a qualitative scale. In 1985, the HCM introduced some general guidelines for calculating bicycle LOS (BLOS) based on the same objective segment attributes for motorized traffic (Transportation Research Board, 1985).

At first, a segment's BLOS did not include any user opinions, relying only on the number of 'events' (i.e., number of pedestrians/other cyclists interfering in a user's movement) (Roess and Prassas, 2014), intending to capture just the obstacles that cyclists came up against along a segment. The inclusion of users' perceptions when measuring cycling infrastructure performance or QoS was first proposed by Botma (1995), shortly after it was modeled with real-time perceptions by Landis et al. (1997). Hummer et al. (2007) then proposed its use in a context of shared spaces. These studies served as a theoretical basis to enhance the HCM BLOS methodology which, despite recognizing the importance of user perception in 2016, still included objective measurements that were detached from travelers' perceptions such as traffic flow characteristics, geometric design, pavement condition, delay at intersections, and average speed on segments (Transportation Research Board, 2016). All of these factors were being implemented in countries of the Global North, with the USA being one of the first to adapt the traditional LOS method to the bicycle.

Overall user perception of cycling infrastructure is affected by several elements. Road safety is one, as the exposure of cyclists to accidents involving motorized vehicles is one of the most common elements measured on different types of infrastructure (Davis, 1987; Pucher, 2001; Sanders, 2015; Thomas and De Robertis, 2013). The presence of cycling infrastructure on an urban street segment greatly improves people's perception of road safety (Dill and McNeil, 2016). Similarly, cyclists' perceived road safety affects cycling frequency and the routes chosen by cyclists when riding (Caviedes and Figliozzi, 2018).

Infrastructure conditions such as paving, signage, and traffic separation are closely related to road safety and are also part of the cyclists' perceived performance. There is evidence showing that the performance or QoS rendered by a location or segment used by non-motorized users can be influenced by the perceptions of the built environment regarding these infrastructure characteristics (Dill et al., 2014; Jensen, 2007; Landis et al., 1997; Petritsch et al., 2007; Titze et al., 2008). However, there are only a limited number of studies dealing with how to measure, analyze, and relate perceptions of tangible attributes with the overall perception of the cycling infrastructure. Since perceptions are based on the user experience of tangible attributes when using the infrastructure (e.g., traffic separation, lane width, or interferences), this may not always match the objective measurements and classifications (Flannery et al., 2006). In addition, there are subjective attributes (e.g., security against theft, comfort, convenience) which cannot be measured objectively on-site, and latent variables that also contribute to the explanation of infrastructure QoS (Calvey et al., 2015; Caviedes and Figliozzi, 2018; Li et al., 2012a). Unbiased user perceptions can be measured by means of data collection through real-time perception surveys applied to people in specific locations of interest (Chaurand and Delhomme, 2013; Landis et al., 1997; Li et al., 2012b). In developed countries several studies have been conducted to capture cyclists' perception of the built environment (Landis et al., 1997; Ma and Dill, 2015; Muhs and Clifton, 2015; Swiers et al., 2017), however, these do not connect the perceptions with how users directly perceive the cycling infrastructure performance. Some of them have assessed cyclists' perceptions through attitudinal variables (de Souza et al., 2014; Xing et al., 2018), while others have attempted to estimate a bicycle comfort index based on these attributes (Ayachi et al., 2015; Kirner Providelo and da Penha Sanches, 2011). Li et al. (2012a) evaluate cyclists' comfort when using two types of cycling facilities using ordered probit models. These are good approaches that have greatly contributed to the literature, however, there is space for further research to analyze the interactions between attitudes, past bicycling experience, and on-site infrastructure perceptions. Also, the literature related to infrastructure quality of service assessment does not explain the relationships between variables using Structural Equation Modeling, a method that has mainly been used to explain travel behavior (Golob, 2003; Van Acker et al., 2014).

The approach based on the Level of Traffic Stress (LTS) was developed more recently in 2012 and has been used in cases where the amount of data needed to calculate BLOS is not available (Mekuria et al., 2012). On a scale of 1 to 4, where 1 corresponds to not very stressful and 4 very stressful, this method rates the stress perceived by a cyclist on segments of a network based on measurements such as motor vehicle traffic, blockage density (i.e., parked cars or stopped buses), number of lanes, traffic separation, width of bicycle lane, speed limit, and intersection types (i.e., protection for cyclists in right or left-turn lanes) (Furth et al., 2016). The LTS scale is based on Geller's four types of cyclist classification (i.e., 'No way no how,' 'Interested but concerned,' 'Enthused and confident,' and 'Strong and fearless'), and has mainly been used and has inspired infrastructure design being adopted as an assessment in many countries, especially in the Global North where cyclist population covers this range of typologies.

The number of interferences is another common element used across methodologies for assigning a performance rating to the cycling infrastructure. Interferences are directly related to the segment's volume of cyclists and pedestrians, and the number of obstacles or hindrances on the route. The influence of this factor on cycling infrastructure QoS was first explored by the HCM which refers to the interferences as 'events,' which were at first the only indicator for grading the BLOS. Botma (1995) suggested that the QoS of a segment of cycling infrastructure is not affected by its capacity but instead by interferences such as pedestrians and other cyclists. Additionally, excessive signaling and intersections forcing cyclists to stop may cause dissatisfaction, primarily due to the energy expended in stopping and accelerating (Fajans and Curry, 2001), and, to a lesser extent, in some contexts, because of perceived insecurity and fear of crime when there are too many traffic lights on a segment, forcing cyclists to stop too often (Johnson et al., 2013).

The built environment has been widely studied in the cycling context, but past literature falls short when referring to assessments carried out in the Global South. Van Houten and Seiderman (2005) found that cyclists' perceived attributes of the built environment when using cycling infrastructure (e.g., aesthetics, odor, noise, landscaping, and corridor greenery) explain cyclist comfort or lack thereof, while Li et al. (2012a) recently investigated the impacts of the physical variables of bicycle facilities on cyclists' perceived comfort, finding significant relationships between this factor and the aspects of the built environment such as road geometry.

The comfort factor is frequently used to explain how cyclists perceive the built environment (Calvey et al., 2015; Li et al., 2012a). Convenience, a similar concept, which is sometimes used interchangeably with comfort, is a positive perception of how the selected infrastructure is serving cyclists on their journey to their destination compared to other options (Piatkowski and Marshall, 2015). The same reasoning applies for car drivers when choosing a route. However, the comfort perceived by drivers varies very little between one route or another since their interaction with the built environment is much lower than that of a pedestrian or a cyclist (Anowar et al., 2017). These two concepts have therefore frequently been grouped together in the same dimension since they have been assessed when comparing the performance between motorized mode alternatives (e.g., vehicles, routes, costs) usually in developed country settings (Imre and Çelebi, 2017). The difference between these two concepts is more fundamental when assessing non-motorized mode actors' perceptions. Convenience is then commonly related to utility variables such as travel time and traffic volume, greatly affecting cyclists' preference for one route over another (Anowar et al., 2017).

An additional subjective attribute commonly related to comfort and convenience is the user's enjoyment when using the infrastructure, captured as a sensorial experience that depends on individual, environmental, and past bicycling behavior (Xing et al., 2018). For example, crime perception may be part of that sensorial experience, but it has not been studied enough at a local level to understand its effects on infrastructure QoS (Akar and Clifton, 2009; Willis et al., 2015). Among the individual factors, personal attitudes represent intangible information that is commonly independent of a specific infrastructure segment. However, activities such as riding a bicycle or commuting by car influence the user's perception of the infrastructure QoS when they are controlled by personal attitudes (Heesch et al., 2015; Schoner et al., 2015; Titze et al., 2008). Although personal attitudes have been studied mostly for mode choice and to explain levels of bicycle commuting (de Souza et al., 2014; Gatersleben and Appleton, 2007; Heinen and Handy, 2012; Kamargianni and Polydoropoulou, 2013; Muñoz et al., 2016), they have also been used to explain the service provided by cycling infrastructures (Willis et al., 2015; Ye and Titheridge, 2017). Specifically, people who enjoy riding a bicycle perceive the infrastructure differently from those who do not (Xing et al., 2018). This enjoyment perception also depends on an individual cyclist's skills and experience (i.e., past cycling behavior) and by attitudes towards specific means of transportation (Dill and McNeil, 2016).

Variables explaining cycling infrastructure service or cyclist enjoyment are often difficult to measure and analyze. Cyclists' perceptions of the infrastructure along with individual attitudes are increasingly used (independently) to improve the planning and design of such infrastructure. There are useful contributions in the literature such as Muñoz et al. (2016) in Vitoria-Gasteiz, Spain, and Majumdar and Mitra (2015) in Kharagpur, India, that use SEM to better explain cyclists' perceptions of the infrastructure. However, the previous uses of SEM methods have not specifically contributed to the measurement of the perceived cycling infrastructure QoS based on the two dimensions of interest emphasized here: infrastructure perceptions and individual attitudes. This research has attempted to measure or explain the perceived cycling infrastructure QoS from a users' perspective based on relationships with attributes found using an SEM approach.

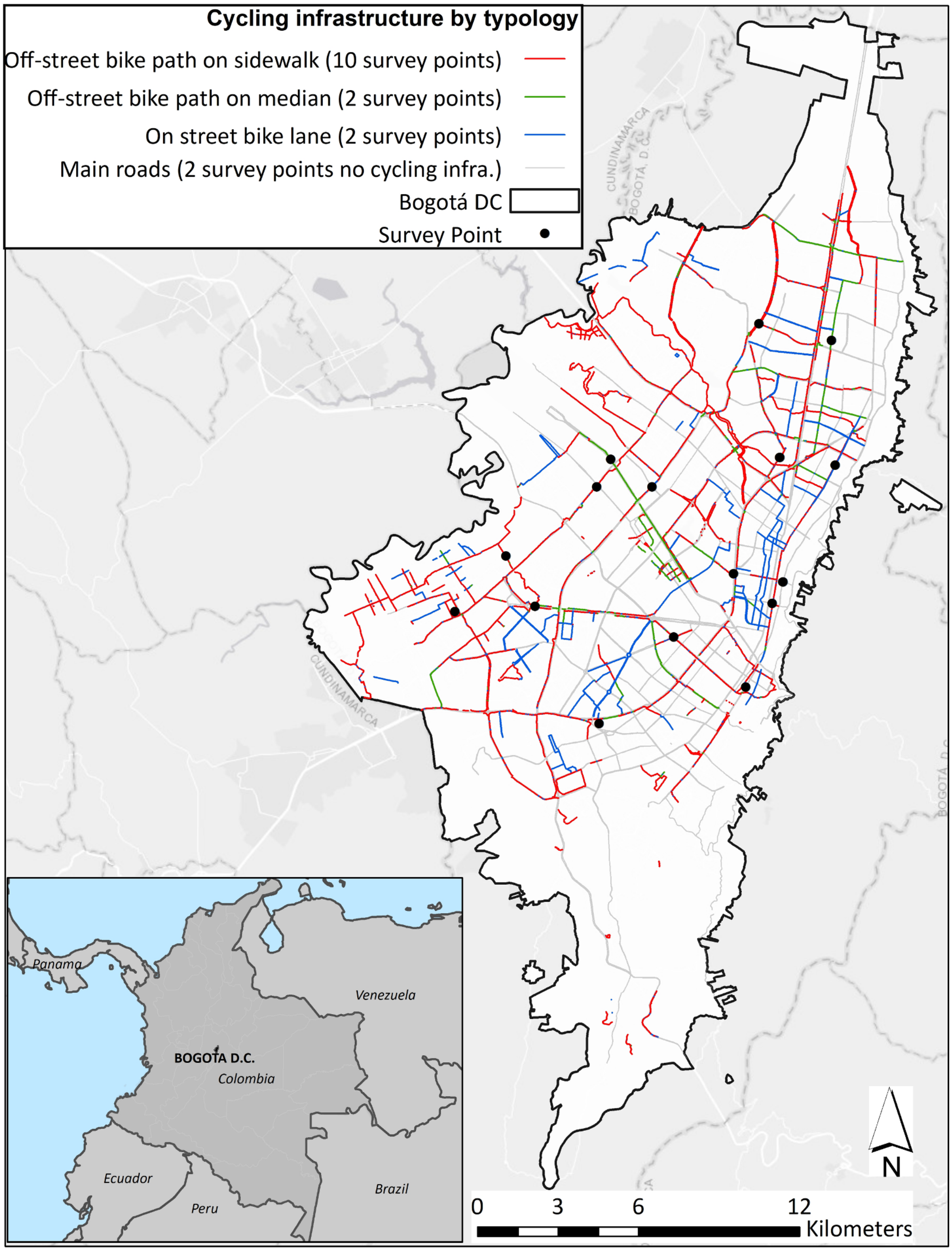

Fig. 1. Cyclist intercept survey locations in Bogotá.

3. Methodology

3.1. Data

A bicycle intercept survey was conducted in 16 different locations in different districts in Bogotá, Colombia, producing a total of 432 valid responses (we were able to obtain at least 25 complete surveys in each location) after the data cleaning process where outliers and missing data were eliminated. The survey locations covered different Zonal Planning Units to attain a diverse sample in terms of physical infrastructure attributes, income ranges, and trip characteristics among the cyclists' population segments in each planning zone, based on the city's 2015 Household Travel Survey (HTS) (see Fig. 1).

Table 1
Cyclist sample composition.

	Survey					
	Paper intercept survey 2017		Cyclists 2011 HTS		Cyclists 2015 HTS	
	n	%	n	%	n	%
Income*						
< $160	58	13.37%	309	16.22%	387	8.58%
$160–$255	89	20.53%	393	20.67%	946	20.97%
$255–$380 USD	81	18.85%	393	20.67%	1323	29.31%
$380–570 USD	92	21.24%	468	24.58%	1252	27.75%
$570–885 USD	44	10.26%	139	7.31%	377	8.34%
$885–1585 USD	39	9.07%	125	6.58%	140	3.10%
$1585–2535 USD	21	4.77%	21	1.08%	81	1.79%
> $2535 USD	8	1.91%	55	2.91%	7	0.16%
Gender						
Male	338	78.13%	1564	82.20%	3417	75.71%
Female	94	21.87%	339	17.80%	1096	24.29%
Age						
< 18	9	2.01%	105	5.54%	72	1.60%
18–24	97	22.36%	397	20.88%	259	5.74%
25–34	117	27.39%	361	18.96%	818	18.13%
35–44	96	22.11%	382	20.07%	1019	22.59%
45–54	69	16.08%	336	17.61%	1133	25.07%
55–64	33	7.54%	197	10.34%	728	16.14%
65–75	9	2.01%	80	4.21%	331	7.34%
> 75	2	0.50%	45	2.39%	153	3.39%
Observations		432		1903		4513

Notes: * Income is in 2017 USD.

We do not claim the sample to be representative, but we do believe that it is indicative of the city's population, as presented in Table 1. However, the 2011 and 2015 HTS (Secretaría Distrital de Movilidad, 2015, 2011) served as a guide to compare the similarity of the cyclists' sample with the entire population related to income range, gender, and age (see Table 1). The survey locations were selected by considering all types of bikeable infrastructures available in Bogotá, grossly classified into four typologies (i.e., off-street bicycle paths [10], on-street bicycle lanes [2], on-street without dedicated bicycle infrastructure [2], and main roads with no dedicated cycling infrastructure [2]). Most off-street bike paths are located on sidewalks and share the space with pedestrians and on medians, both separated from motorized traffic. This is the most common cycling infrastructure in the city and was built up until the early years of the 2010 s. Since 2014, cycling infrastructure has been implemented on the streets, taking space away from cars. Two survey points were located on this type of infrastructure, where cyclists ride on the street and are protected from traffic using physical separation. The remaining two survey points were located on roadways with no cycling infrastructure but with high volumes of cyclists. Taking into account that Bogotá has dry and rainy periods, but that these "seasons" are quite variable, and that Bogotá's weather is fairly constant throughout the year, surveys were applied between April 24 and May 17, 2017, during working days. The time periods for the surveys were: morning (06:45–09:30), noon (11:00–13:45), and afternoon (16:00–18:00). Each survey lasted approximately eight minutes and the overall response rate was 27.5%. Surveyors picked one out of every three passing cyclists to respond and, in this way, attain randomness.

The four-section questionnaire was applied in the following order—starting from general to specific, aiming to avoid the anchoring effect (Dillman et al., 2014)—: attitudes, infrastructure perceived performance, environment perception, and socio-economic information. A description of all the variables the respondents were asked about and were used in this study are shown in Table 2. The cyclists were first asked about their overall perceived QoS of the specific street segment ('infrastructure service') as the most general question. This is the independent variable selected for this study. Questions relating to infrastructure and attitudinal-related statements were based on a 1–5 point Likert-based scale (1 being strongly disagree and 5 strongly agree), except for the paving, signaling, and traffic lights questions (which are Likert-based questions, 1 being poor and 5 excellent). Slope perception of the segment was not included in the questionnaire, given that Bogotá's topography is predominantly flat, and all survey points were, in fact, slope-free, therefore, there were no differences between them. At the end of the survey, cyclists were asked a number of socio-demographic questions, which were left out of the analysis since the research objective focuses mainly on the QoS variable, attitudinal inquiries, and infrastructure-related perceptions, leaving out control variables such as age and gender.

3.2. Modeling approach

To study the effect of user perception of physical attributes of the infrastructure, built environment, and attitudes on the overall perception of QoS, we developed an SEM approach that identifies latent variables from subjective attributes to be used in the same model (Ortúzar and Willumsen, 2011). To develop the SEM approach, we initially carried out an exploratory factor analysis (EFA)

Table 2
Variable descriptions.

Type	Variable	Statement/Question	Range
Performance	Infrastructure service (QoS)	How good is the service provided by this cycling infrastructure?	1–5
Attitudinal	Likes cycling	I like to ride a bicycle.	1–5
	Exercise is important	Regular exercise is important to me.	1–5
	Street vendors	When I ride a bicycle, street vendors get in my way.	1–5
Infrastructure	Paving	How good is the paving on this cycling infrastructure segment?	1–5
	Signaling	How good is the signaling on this cycling infrastructure segment?	1–5
	Traffic lights	How good are the traffic lights on this cycling infrastructure segment?	1–5
	Greenery	I like tree-planting on this cycling infrastructure segment.	1–5
	Roadway preference	When I use this cycling infrastructure segment, I prefer to ride on the road.	1–5
	Safety	I feel safe from accidents along this cycling infrastructure segment.	1–5
	Bicycle flow	The number of cyclists stops me from riding freely.	1–5
	Pedestrian flow	The number of pedestrians stops me from riding freely.	1–5
	Security	I feel safe from robbery along this cycling infrastructure segment.	1–5
	Enjoyment	Moving along this segment is pleasant.	1–5

using the variables identified in Table 2, enabling us to identify the latent variables (for the sake of clarity, latent variables will be written in italics) that explain the different indicators, where the labels assigned to them are subjective. For the EFA, a PROMAX oblique rotation method was assumed to permit correlations between latent variables, and the number of latent variables was determined using the scree test criterion. Table 3 illustrates the PROMAX rotated component analysis factor matrix.

Four latent variables (i.e., *attitudes*, *convenience*, *interferences*, and *infrastructure*) were hypothesized from the factor loadings presented above. The latent variables were hypothesized using the following indicators for identification: *attitudes* from two attitudinal questions (i.e., likes cycling and exercise is important); *convenience* from questions related to elements that make the use of a particular segment of infrastructure convenient (i.e., greenery, roadway preference, safety, and security); *interferences* from cyclist interaction with others (i.e., street vendors, bicycle flow, and pedestrian flow); and, *infrastructure* from questions related to the infrastructure elements (i.e., signaling, traffic lights, and paving). However, in the last latent variable, all factor loading indicators are positive, despite the fact that in the literature, signaling and traffic lights are assumed to be negative, while paving is assumed to be positive for cyclists. Accordingly, we decided to swap *infrastructure* with a new latent variable called *signaling*, which can be identified based on the questions that refer to the appropriateness of signaling and traffic lights. Then, based on the EFA results and the SEM assumption of temporal precedence between the established relationships (Hoyle, 2012), we developed an SEM model. For the SEM model we initially hypothesized that all latent variables and the perceived attributes not used to identify latent variables (i.e., paving and enjoyment) would have a direct effect on the perceived QoS, reserving only the relationships with significant parameters (i.e., absolute z-values higher than 1.64). Then, in the cases where direct effects were not significant, we also tested the indirect effects.

This methodological approach has been applied in the past in transportation services and infrastructure such as airport terminals (Bezerra and Gomes, 2016; Losekoot, 2015), pedestrian infrastructure (Bivina and Parida, 2019; Cantillo et al., 2015; Said et al., 2017; Vallejo-Borda et al., 2020b), and public transportation (de Oña and de Oña, 2015). Besides, SEM models have also been used through a latent variable identification without defining the latent variables from objectively measured attributes (e.g., demographic variables) (Bivina and Parida, 2019; Jahan et al., 2020; Vallejo-Borda et al., 2020a).

SEM is a statistical modeling tool that can be used as an extension of linear models (Lei and Wu, 2007; Vallejo-Borda et al., 2020a). The way in which intangible elements were captured allows us to use the responses as an interval, supporting the previously mentioned linear assumption. In other words, we have both latent variables and variables the respondents were asked about, as dependent variables, that are not assumed as ordered. The main reason for this is that we collected cyclists' responses in a 1–5 Likert-based scale (i.e., numeric scale), where cyclists can identify equal spacing between the possible responses (Wu and Leung, 2017). SEM

Table 3
PROMAX rotated factor loadings.

	Factor1	Factor2	Factor3	Factor4
Likes cycling	−0.024	0.105	0.078	**0.664**
Exercise is important	0.043	−0.069	−0.052	**0.259**
Greenery	0.163	**0.183**	−0.144	−0.096
Roadway preference	0.099	**−0.513**	0.049	0.054
Safety	−0.041	**0.626**	0.010	0.094
Security	−0.084	**0.464**	0.088	0.081
Street vendors	−0.068	0.079	**0.278**	−0.177
Bicycle flow	0.006	−0.258	**0.226**	−0.012
Pedestrian flow	0.024	0.009	**0.877**	0.061
Signaling	**0.936**	−0.038	0.014	−0.016
Traffic lights	**0.492**	0.004	0.031	0.028
Paving	**0.284**	0.364	0.080	−0.020

Note: Selected loading associated with each factor are presented in bold font.

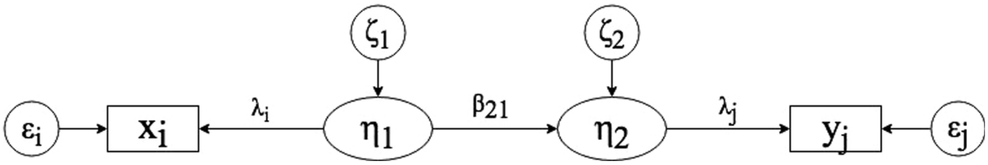

Fig. 2. SEM generic model structure.

can be notated as follows:

$$y_j = \alpha_j + \lambda_j \eta_2 + \varepsilon_j \tag{1}$$

$$x_i = \alpha_i + \lambda_i \eta_1 + \varepsilon_i \tag{2}$$

$$\eta_2 = \beta_{21} \eta_1 + \zeta_2 \tag{3}$$

Fig. 2 presents a generic model with two latent variables (η_1 and η_2), and i and j common-factors or attributes (x and y). The common-factors are a function of two variables, where one of them is common to all (η_1 or η_2) and can be calculated using Eqs. (1) and (2), where y is the perceived QoS, x_i represents the attributes, 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 respectively, and ε is the error in the measurement equation for x or y with an expected value of zero. For this study, the x indicators represent the street segment-related perception statements presented in Table 2, and y indicators illustrate cyclist perception of QoS when riding. Additionally, latent variable η_2 is a function of the latent variable η_1 and can be calculated using Eq. (3), 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, and ζ is the random error for the latent variable with a mean expected value of zero. For this study, all errors were assumed to be normally distributed. 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 (see Table 4) (Bollen, 2014; Hoyle, 2012; Lei and Wu, 2007). We estimated the SEM model using the R function "sem" of the "lavaan" package (R Core Team, 2019; Rosseel, 2012).

4. Results

Our measurement model comprises four latent variables explained by eleven attributes measured using cyclist perceptions. The latent variable identified by the largest number of indicators is *convenience* (i.e., greenery, roadway preference, safety, and security), followed by the latent variable related to the *interferences,* which was identified using three different indicators (i.e., street vendors, bicycle flow, and pedestrian flow). The latent variable related to the cyclists' perception of *signage* was identified using two different attributes (i.e., signaling and traffic lights). Finally, the latent variable related to cyclists' *attitudes* was identified based on two indicators (i.e., likes cycling and exercise is important). The significance of the different indicators associated with the latent variables is shown in Table 5.

The variance–covariance matrix resulting from the measurement model reflects the correlations obtained between different indicators (see Table 6). As expected, the indicators of the same latent variables are highly correlated. There is a negative correlation between the cyclists' perception of greenery on the infrastructure and the perceived obstacles attributed to pedestrian flow. Finally, correlations were found between the indicators of latent variables *convenience* and *signage*. This last finding was to be expected considering that the EFA rotation method allowed correlations between latent variables in order to represent a more realistic model.

The SEM analysis using the latent variables and the individual users' perception variables associated with paving, enjoyment, and QoS (not included in the latent variables) implies that cyclists' perceived QoS is directly influenced by the perceived infrastructure quality (*signage* and paving) and the perceived emotion of pleasure or enjoyment (hereafter referred to as enjoyment) that cyclists experience when riding a segment. In addition, cyclists' perception of *signage* in the infrastructure (measured using perceptions of signaling and traffic lights) accounts for the greatest direct and indirect positive impact on the perceived QoS of all the latent variables. Infrastructure *signage* also has an impact on the perception of paving and enjoyment, improving perceived QoS indirectly given the positive relationships between QoS, enjoyment, and *convenience* as was established in the literature.

The final model suggests that cyclists' enjoyment is affected by the way they perceive the infrastructure in terms of *signage, convenience*, and *interferences*, and by their own *attitudes* towards cycling and exercise. Considering these latent variables, a direct

Table 4
Goodness of fit indicators of an SEM model.

Indicator	Explanation	Accepted threshold
χ^2/DF	Measures the discrepancy between the sample and model covariance matrices corrected for degrees of freedom.	$<$ 3.000
RMSEA	Determines the model fit to the covariance matrix of the sample with unknown coefficients.	$<$ 0.060
CFI	Compares the proposed model with a non-correlated model between latent variables.	$>$ 0.950
TLI	Compares the mean square from the proposed model with a baseline model.	$>$ 0.950
SRMR	Calculates the square root of the difference between the sample and the hypothesized model covariance matrices residuals.	$<$ 0.080

Table 5
Standardized parameters of the measurement model.

Latent variable	Observed variable	α	λ	z-value
Attitudes	Likes cycling	11.854	0.455	3.653
	Exercise is important	5.713	0.472	3.672
Convenience	Greenery	2.545	0.520	11.429
	Roadway preference	1.314	−0.378	−7.648
	Safety	2.830	0.578	12.902
	Security	2.037	0.225	4.163
Interferences	Street vendors	1.770	0.321	5.009
	Bicycle flow	1.730	0.431	6.388
	Pedestrian flow	1.779	0.669	7.902
Signage	Signaling	2.408	0.659	13.938
	Traffic lights	2.930	0.477	8.889

Table 6
Variance-covariance matrix of the measurement model.

	A1	A2	C1	C2	C3	C4	I1	I2	I3	S1	S2
Likes cycling (A1)	0.169										
Exercise is important (A2)	0.070	0.623									
Greenery (C1)	−0.021	−0.042	2.095								
Roadway preference (C2)	0.014	0.029	−0.392	1.893							
Safety (C3)	−0.021	−0.042	0.565	−0.391	1.690						
Security (C4)	−0.009	−0.018	0.243	−0.168	0.503	2.057					
Street vendors (I1)	0.003	0.006	−0.109	0.075	−0.109	−0.047	2.347				
Bicycle flow (I2)	0.004	0.007	−0.126	0.087	−0.126	−0.054	0.279	1.732			
Pedestrian flow (I3)	0.006	0.012	−0.579	0.155	−0.224	−0.096	0.496	0.573	2.274		
Signaling (S1)	−0.002	−0.004	0.497	−0.343	0.495	0.213	−0.153	−0.177	−0.314	1.624	
Traffic lights (S2)	−0.001	−0.003	0.354	−0.245	0.354	0.152	−0.109	−0.126	−0.224	0.724	1.582

negative effect of enjoyment is indicated, caused by *signage*. However, the strongest effect in terms of enjoyment comes from the *convenience* latent variable comprising the location’s intangible features, such as the perception of road safety and greenery. The latter causes *signage* to have an indirect effect on enjoyment that is positive and greater than the direct effect, causing an overall positive total effect on cyclists' enjoyment (see Table 7). Cyclists' perceptions of *signage* on cycling infrastructure also positively affect their perception of paving and *convenience* when riding. Similarly, the model suggests that cyclists with positive *attitudes* towards cycling and exercise will feel greater enjoyment when riding.

The *interferences* perceived by cyclists when riding is the only perception of a latent variable that explained a decrease in all the other latent variables and attributes. This means that when cyclists’ perception of interferences is good, they become annoyed with other transportation modes. The final model, shown in Fig. 3, suggests that if the cyclists' perception is that there are a high number of interferences, this will have a negative impact on the perception of the infrastructure *signage*. This more negative perception of *signage* leads to a more negative perception of the infrastructure's *convenience*, which in turn negatively impacts levels of enjoyment and QoS. The model revealed that attitudinal variables such as whether the individual likes to ride a bicycle or whether he or she considers that exercising is important, lead to greater enjoyment when riding and do not depend on other latent variables.

The final model presents a satisfactory adjustment and no modifications were made after the evaluation of the resultant model which revealed its good data fit (see Table 8).

5. Analysis and discussion

SEM approaches for understanding user perception of QoS of any transportation system used to be employed exclusively for public transport (De Oña et al., 2013). This statistical approach to bicycle type infrastructure delivered reliable results that described user perception and connected them with personal characteristics such as attitudes. The QoS model both confirms and contests findings in the literature concerning cycling infrastructure performance. The relative importance of the attributes most closely associated with perceived QoS, such as paving along the route and personal enjoyment when using it, reveals some of the priorities cyclists subconsciously bear in mind when riding along a bicycle corridor. In this sense, HCM approaches were partly correct in including quality parameters such as the International Roughness Index (IRI) to assess the performance of a cycling segment, however they fall short when accounting for sensory experiences along the route from the users’ perspective, and more importantly, they leave out the enjoyment aspect. The model confirms that individual attitudes directly interact with cyclists’ enjoyment and are indirectly connected to their perception of convenience related to tangible attributes of the infrastructure.

Cyclists’ behavior in choosing the roadway over the segregated bicycle infrastructure statistically explains user QoS, through the *convenience* latent variable. Past research showed that the most common attributes that lead users to choose between riding on a

Table 7
Effects of the SEM bicyclist perceived QoS final model.

	β and λ						α
	paving	enjoyment	*Attitudes*	*Convenience*	*Signage*	*Interferences*	
Direct							
infrastructure service (QoS)	0.238	0.150			0.482		1.802
(z-value)	(3.495)	(3.123)			(5.399)		
paving					0.617		2.565
(z-value)					(12.442)		
enjoyment			0.325	1.223	−0.671		3.222
(z-value)			(2.409)	(3.802)	(−2.010)		
Convenience					0.783		
(z-value)					(12.177)		
Signage						−0.371	
(z-value)						(−4.717)	
Indirect							
infrastructure service (QoS)			0.049	0.183	0.190	−0.249	
(z-value)			(1.899)	(2.346)	(4.586)	(−4.179)	
paving						−0.229	
(z-value)						(−4.386)	
enjoyment					0.958	−0.106	
(z-value)					(3.026)	(−2.544)	
Convenience						−0.290	
(z-value)						(−4.365)	
Total							
infrastructure service (QoS)	0.238	0.150	0.049	0.183	0.672	−0.249	
(z-value)	(3.495)	(3.123)	(1.899)	(2.346)	(11.191)	(−4.179)	
paving					0.617	−0.229	
(z-value)					(12.442)	(−4.386)	
enjoyment			0.325	1.223	0.287	−0.106	
(z-value)			(2.409)	(3.802)	(2.921)	(−2.544)	
Convenience					0.783	−0.290	
(z-value)					(12.177)	(−4.365)	
Signage						−0.371	
(z-value)						(−4.717)	

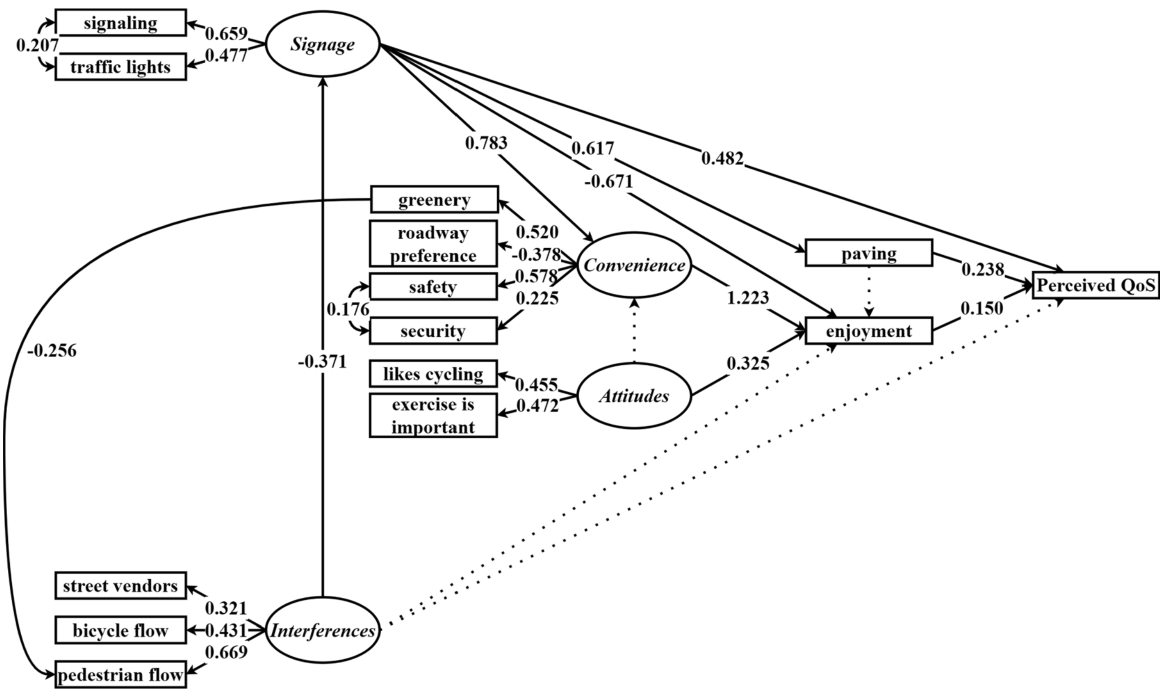

Fig. 3. SEM infrastructure QoS final model.

Table 8
Goodness of fit indicators of the final model.

Indicator	Model result	Accepted threshold
χ^2/DF	1.090	< 3.000
RMSEA	0.015	< 0.060
CFI	0.994	> 0.950
TLI	0.991	> 0.950
SRMR	0.033	< 0.080

roadway or dedicated bicycle infrastructure are traffic volume and travel time (Anowar et al., 2017), which are clearly associated with the *convenience* latent variable that is negatively related to cyclists' "roadway preference" variable (Piatkowski and Marshall, 2015)

Previous studies have shown the importance of understanding cyclists' perceptions of the infrastructure's physical and intangible attributes (Heinen et al., 2011; Xing et al., 2018). The aspects traditionally considered for measuring infrastructure QoS are objective physical variables (e.g., width or separation from the traffic stream), measurable interferences (e.g., motorized traffic intersections) or even statistical reports about road accidents and thefts. However, perceptions of a specific place could differ between people or times of day, and not reflect the findings of the statistical reports. For example, segments that seem secure for some cyclists may be subject to a high rate of daily thefts or crimes. However, the scarcity of studies exploring these relationships using perceptions suggests that there is still a gap in the research that could potentially be filled. In addition, SEM models have not been widely used specifically to understand relationships between cyclists' perceptions of infrastructure attributes and the overall infrastructure QoS, personal *attitudes*, and enjoyment. The results obtained through the SEM model that only considers the cyclists' point of view allows us to deepen our understanding of infrastructure QoS and the relationships which explain it.

Interferences or hindrances caused, for example, by pedestrians (Botma, 1995; Li et al., 2012b), by other cyclists (Li et al., 2012b), and by street vendors affect cyclists' freedom to maneuver and consequently the perceived infrastructure QoS. Street vendors and pedestrians, common in a Global South city context, are analogous to areas with office blocks and high commercial land use in Global North countries and these too are negatively associated with cyclists' segment comfort. This finding is compounded with the BLOS measurement of the HCM which, at first, relied only on cyclist interference or 'events' (Transportation Research Board, 1985). Since 12 out of 16 survey points took place on off-street segments, motorized traffic volume was not an issue for cyclists when riding along segments. It has already been shown that motorized traffic volume is a distressing variable in cyclists' perception of quality of service of on-street facilities (Aldred et al., 2017; Mekuria et al., 2012).

However, *interferences* caused by other cyclists affect all types of bicycle infrastructure QoS, as has been shown in past research (Li et al., 2012b). In addition, *interferences* is the only latent variable identified that has a negative effect on cyclists' enjoyment and QoS. Accordingly, an increase in the perceived *interferences* results in reduced enjoyment and QoS for cyclists. However, the negative correlations between the *convenience* variable greenery and the *interference* variable pedestrian flow (see Fig. 3) indicate that improving the cyclists' perception of greenery (e.g., increasing tree planting density along cycling infrastructure rights of way) reduces their perception of *interferences,* producing an overall positive effect on cyclists' feeling of enjoyment and consequently in their perceived infrastructure QoS.

A major result of the model is the power of users' attitudes for indirectly explaining QoS. Previous studies have reported the significant effects of people's attitudes on their decision to use travel modes such as cycling (Heinen et al., 2011; Xing et al., 2018), walking (Kamargianni and Polydoropoulou, 2013), transit, and cars (Domarchi et al., 2008; Verplanken et al., 1994). In addition, controlling for attitudinal variables is good practice that has recently been applied in the analysis of various non-motorized modes of travel behavior, and is currently a topic for discussion (Dill and Voros, 2007; Li et al., 2013). For active travel, there is a general consensus on the importance of attitudes in the decision of whether to cycle and the increasing role of latent attitudinal variables in explaining bicycle mode choice (Akar and Clifton, 2009; Eash, 1999; Muñoz et al., 2016; Rodriguez-Valencia et al., 2019). Results suggest that attitudes regarding riding a bicycle or exercising greatly determine users' experiences when using any infrastructure (regardless of whether it has dedicated linear cycling infrastructure or not). The *attitudes* latent variable appeared to have a direct effect on cyclists' enjoyment, but it did not show a significant causal effect on *convenience*. However, the effect of *attitudes* is smaller by almost 75% compared to the effect of the latent variable *convenience*. Thus, to shift such attitudes, public policy programs such as the Sunday Ciclovía event are ideal for developing positive dispositions towards cycling or doing exercise (Sarmiento et al., 2010), and consequently improving the perceptions of the infrastructure QoS.

Concerning infrastructure *signage*, the literature showed that excessive signage produces dissatisfaction because of having to continually stop and start cycling (Fajans and Curry, 2001), and because of the perceived insecurity or fear of crime which does not always coincide with the reported number of thefts (Majumdar and Mitra, 2015; van Lierop et al., 2015). This direct negative effect on enjoyment can also be found in our final model. However, the model suggests that if *convenience* is used as a mediator, the indirect effect on enjoyment caused by the infrastructure *signage* is greater, generating a positive impact on the perceived infrastructure QoS. The model also suggests that the improvement of latent variable *signage* attributes, such as signaling or traffic lights, has a direct and positive impact on the service provided by the infrastructure. Also, the strong correlation between the perceived attributes of signaling and traffic lights (see Fig. 3 and Table 6) shows that asking users to rate these two separately, and in doing so, identify the differences between them is a challenge for researchers. Presumably, when asked "How good are the traffic lights on this cycling infrastructure segment?", cyclists include traffic lights in their perception of infrastructure *signage*, but not otherwise. The latter makes it difficult, when they are asked "How good is the signaling (vertical and horizontal) on this cycling infrastructure segment?", to identify whether horizontal and vertical signaling throughout the infrastructure is what decreases their enjoyment (-0.671) or whether it is the traffic lights that make them stop at each intersection.

The final model suggests that to understand and satisfy cyclists' needs, their perceptions of *convenience* on the infrastructure segments should be considered, for example, by providing information that is more valuable than related statistical records on the number of accidents or thefts along the segment. The latent variable *convenience* depends on the perception of road safety, road security, preference of riding on the road instead of the cycling infrastructure, and greenery. Personal security (crime) has not been broadly studied on the urban microscale (street scale) since it is difficult to find enough measured crime information at that level. In addition, the correlation found between perceived security and road safety (see Fig. 3) reveals that when asking users to rate these two separately, identifying the differences between them is a challenge for researchers too. Based on the final model results, we suggest that personal security explains a large proportion of the *convenience* component, along with road safety, roadway preference, and greenery perception. These all deserve special attention to understand their local-level effects. Additionally, the difference between latent variable *convenience* and the comfort construct—frequently used in SEM models—was evidenced, as there is no statistical relationship between *convenience* and paving. However, *convenience* presented a strong relationship with greenery, which is an aesthetic element of the infrastructure, sustaining the conceptual debate between this latent variable and its observed variable. In any case, for the cyclists in this study, good greenery, safety, and security are attributes that improve their perception of the *convenience* of the infrastructure, leading to greater enjoyment and a better infrastructure QoS perception.

Although these findings are based solely on existing cyclists' responses on street segments, similar perceptions and behaviors can be obtained from new cyclists on any infrastructure type. It is also recommended to ask and compare cyclist opinions about their general experience when riding a bicycle and specific route characteristics they frequent. Similarly, the results obtained will probably not apply to non-cyclists since this population comprises people that have very different personal attitudes, socio-economic characteristics, and cycling ability when compared to actual cyclists, which conditions infrastructure perceptions (Handy et al., 2007; Heinen and Handy, 2012). Thus, additional efforts are recommended for the identification of infrastructure characteristics that would attract new cyclists to this mode of transportation.

6. Conclusions

This research paper explores the relationships between cyclists' perceptions of the cycling infrastructure attributes along with their personal attitudes and the overall perceived infrastructure QoS. The SEM model presented here reveals that perceptions of physical elements and personal attitudes can statistically explain the overall perception of QoS of any type of infrastructure for cyclists. The model was used to inquire about the relationships between four latent variables, enjoyment, paving, and infrastructure QoS, and statistical relationships were found between them. For instance, perceptions of paving and *signage* have a strong effect on perceptions of infrastructure QoS, however, an unexplored variable that concerns the cyclists' enjoyment when riding along any type of infrastructure also contributes to explaining this effect.

A number of actions that can increase QoS can be based on users' subjective attributes and go beyond providing wide paths, segregated from traffic, calming motorized traffic, reducing interferences, and providing buffer areas between the cycling infrastructure and the traffic roadway. A wide range of possible actions aimed at improving cyclists' perceptions is open to discussion. Two main fields attract our attention: firstly, the direct contribution of "enjoyment" caused by a perception of aesthetic attributes, of intangible conditions, and *attitudes*; and secondly, the clear chain of effects on QoS derived from the perceptions of physical attributes (paving, *signage*, *interferences, convenience*), previously reported in the literature. For example, by improving the perception of greenery (one of the *convenience* attributes), the perceived interferences caused by pedestrians decrease (see Fig. 3), improving enjoyment and perceived QoS. Thus, in high-volume pedestrian areas, which in developing countries usually coincides with high intensity commercial areas and a high presence of street vendors, greenery could mitigate the negative impact caused by these interferences. The latter is a more helpful, easier and cheaper alternative than strongly modifying the built environment and land uses of the infrastructure's surroundings which is often too difficult to change. If, for any reason, *signage* on cycling infrastructure is not well perceived by cyclists, it can be amended if cyclists perceive the infrastructure as convenient by improving the *convenience* (i.e., improving segment greenery, road safety, and security).

Three direct effects positively impact infrastructure QoS as perceived by cyclists: *signage*, enjoyment, and paving. The attributes related to the latent variable *signage* have the greatest impact on the perceived QoS and this perception can be improved by enhancing the perception of the infrastructure's paving conditions. Three latent variables affect cyclists' perception of enjoyment. Two of these are represented positively (*convenience* and *attitudes*), while the other is represented negatively (*signage*). To improve cyclists' enjoyment of any type of infrastructure, their perceptions of *convenience* and their personal *attitudes* are to be considered in future assessments. Additionally, for *signage* density along cycling infrastructures, a careful balance should be found between the necessary information to be shared with cyclists and the oversaturation of signage elements that cause a negative direct effect on their enjoyment. This is reinforced by the model which shows that perceived interferences do not directly affect the QoS but they do indirectly affect the perceived QoS of the infrastructure through the latent variable *signage*.

The model suggests that a second perspective based on user perceptions and attitudes, different from the objective indicator measures such as the well-known HCM LOS or the LTS indicator, can statistically explain the perception of infrastructure QoS. Objective measures tend to ignore attributes, constructs, and intangible measurements such as cyclists' attitudes and perceptions that have an effect on the subjective measure of perceived infrastructure QoS. However, objectively measured information from the cyclists (e.g., demographic variables) can be used as moderators to improve the understanding of the differences in the latent variable effects. For this reason, further research could explore existing correlations between measured and perceived variables and even consider the heterogeneous effects of the cyclists and infrastructure typologies, to enhance our understanding of both objective and intangible attributes. In the scarcity of research on bicycle infrastructure quality of service based on perceptions in the Global South, this study also serves to trigger a discussion on similarities and differences in different geographical contexts such as those found in North America and the northern European countries.

CRediT authorship contribution statement

Jose Agustin Vallejo-Borda: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing - original draft. **Daniel Rosas-Satizabal:** Conceptualization, Methodology, Formal analysis, Validation, Writing - original draft. **Alvaro Rodriguez-Valencia:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft.

Declaration of Competing Interest

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

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