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Pedestrians-Cyclists Shared Spaces Level of Service: Comparison of Methodologies and Critical Discussion

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Abstract: Pedestrians–cyclists shared spaces, sidewalks and streets are now a commonly implemented urban design solution in many cities, due to the willingness to promote sustainable mobility and the non-availability of public space. The proper design and management of these infrastructures requires an accurate evaluation of their performance. The most dominant evaluation metric is the level of service (LOS) and various methodologies have been proposed in the literature for its assessment in infrastructures that are being used by pedestrians, cyclists or by both of these two types of users. The present paper gathers and presents various methodologies, and it applies some of them on two pedestrians-cyclists shared spaces in a medium-sized city in Greece. The outcomes of the methodologies are being compared both among themselves and in relation to the opinions of the users, who participated in a questionnaire survey. The review of the literature, along with the application of some of the methodologies, leads to a fruitful discussion, which sets the groundwork for future research in the field of LOS and it also assists practitioners in selecting the appropriate methodologies for the assessment of pedestrian–cyclists shared spaces.

Keywords: urban mobility; pedestrians; bicycles; shared space; level of service; LOS; road traffic engineering

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1. Introduction

The present paper deals with the various methodologies that exist for assessing the level of service (LOS) that is provided by pedestrians–cyclists shared streets and spaces and sets a critical discussion around these methodologies. Shared streets and spaces, i.e., the coexistence of different categories of users in a single infrastructure, are not new concepts. On the contrary, the streets, traditionally, have been a place of interaction between people, where the social, cultural and economic life of cities took place [1]. However, the evolution of the automotive industry and the rapid introduction of motor vehicles in the transportation systems over the last century have created new challenges and the priority in transportation and urban planning was to serve greater volumes of motorized traffic and achieve higher speeds for the vehicles. This planning gradually contributed to the separation of different categories of road users and to the tendency of rendering exclusive lanes to each one of them, giving priority to motor vehicles [2].

The first attempts to rearrange streets and integrate traffic into social space were made in the late 1960s by Dutch scientists [3]. In recent years, it has begun to be understood by transport planners and decision makers that the implementation of exclusive lanes for each category of road users is extremely difficult, due to the limited public space [4] and that there is a need for strengthening the role of the street in terms of social interaction [1]. Thus, today there is a tendency to redistribute the urban environment in favor of pedestrians and "soft" transport modes, as well as to turn streets into places of activity and interaction of people, as expressed in the latest version of the guidelines for the implementation of Sustainable Urban Mobility Plans [5]. In this direction, more and more cities are implementing pedestrian–bicycle shared infrastructures.

Many research efforts have been made to identify whether pedestrians–cyclists coexistence and shared infrastructures are safe and whether this arrangement is a preferred option over bicycle traffic on roads, where they coexist with motorized traffic. One of the first research efforts to investigate the safety level of these infrastructures was that of Aultman-Hall and LaMondia [6], who collected data about accidents and exposure through a questionnaire survey, in order to calculate indicators for three shared infrastructures in the U.S. Their results show that the majority of accidents are falls and not collisions, while in particular collisions between pedestrians and cyclists are a rare phenomenon [6]. Chong et al. [7] used deaths data for New South Wales, which are recorded in the Australian Bureau of Statistics, as well as injuries data collected from all public and private hospitals in the same State, with the aim to compare the severity of collisions between bicycles with motor vehicles and between bicycles with pedestrians. Their statistical analysis leads to the conclusion that the risk of injury is higher for cyclists who collide with a motor vehicle, but collisions between pedestrians and bicycles can also lead to serious injuries, while the risk of serious injury is higher for pedestrians and cyclists aged over 65 years [7]. The same research team, a year later, published a study aimed at quantifying the risk of injury or death from pedestrian-bicycle collisions and concluded that the probability of death is almost zero, while the probability of injury is as rare as the probability of death in a plane crash [8]. A more recent study in Australia, specifically in Melbourne, focuses on pedestrian injuries due to collisions with bicycles, finding that, from 2006 to 2016, there was no increase and that the frequency of these injuries is extremely low, especially compared to the frequency of pedestrian injuries from a collision with a motor vehicle [9]. Particularly interesting is the analysis by Varnild et al. [10], which investigates all pedestrian and cyclist injuries during the period 2003–2017 in Sweden, where the "Vision Zero" road safety policy was implemented. Using statistical tools, they identified that both pedestrians' injuries and serious cyclists' injuries are significantly rarer off the road, where there is no interaction with traffic, and conclude by recalling the suggestion of the "Vision Zero" policy to separate unprotected road users from the motorized traffic [10]. Finally, it should be mentioned that the interaction of pedestrians and cyclists has become greater during the last years, due to the extensive implementation of bike-sharing schemes, which in many cases require the installation of stations on sidewalks [11–13].

In any case, for the successful design and management of the infrastructures used by pedestrians, cyclists or both of these categories of users, the application of appropriate methodologies for assessment is required [14–16]. For this reason, various evaluation metrics have been developed and established. Some of them refer to pedestrians (e.g., walkability index and walkscore), while others refer to cyclists (e.g., bicycle safety index rating, bicycle compatibility index and bicycle environmental quality index) [17,18]. However, the two most established metrics for evaluating pedestrian and bicycle infrastructure are the level of service (LOS) and the quality of service (QOS). The concept of LOS for pedestrians (but also for vehicles) is very closely linked to the density of users in the infrastructure. This is also reflected in established sketches that attempt to express the different levels of service. Thus, LOS A, which is the ideal condition for the user, expresses a state of low user density and speed equal to that in free flow conditions, while LOS F expresses an unfavorable situation, where saturation conditions have occurred [19]. Based on the above, it is understood that an infrastructure with a high LOS is not necessarily a well-designed infrastructure that offers satisfactory levels of safety and comfort [20]. On the contrary, a high LOS could be a consequence of the low frequency of the use of an infrastructure, which could also indicate the reluctance of travelers to use that infrastructure [17]. However, according to the Highway Capacity Manual [21], the QOS describes whether an infrastructure works well, from the perspective of the users and therefore the concept of QOS extends to that of LOS.

However, it should be noted that the term "LOS" has dominated, and in many research papers, its meaning goes beyond the narrow limits of the description of the available space for each user and converges more on the definition of the term "QOS". Thus, LOS and QOS can be thought of as concepts (i.e., abstract ideas), and as stated by Tate [22], concepts can be described by researchers through qualitative data and quantitative measures.

The goal of the present paper is to present the various methodologies that exist for calculating pedestrian LOS, bicycle LOS and pedestrians-cyclists shared space LOS, as well as to discuss their advantages, disadvantages and to set the ground for future research in the specific field. Moreover, the paper investigates the suitability of the different categories of methods for the assessment of pedestrians-cyclists shared space. Therefore, the paper aims to assist not only researchers, but also practitioners who have the responsibility of assessing and designing shared sidewalks or streets for pedestrians and cyclists. Assisting the assessment of pedestrians-cyclists shared spaces will contribute to enhancing the sustainability of urban transportation systems, since the design and management of these infrastructure will be made in a more effective way and as a result walking and cycling, which offer significant environmental, economic and social benefits, will become more preferable mobility options.

2. Literature Review

2.1. Pedestrian LOS

Numerous surveys have been carried out with the aim of investigating the pedestrian LOS and formulating appropriate methodologies. These methodologies utilize field measurements, interviews with experts and questionnaires, while most of them use statistical modeling or point system techniques. According to a recent literature review [23], 60% of the pedestrian LOS models have come through regression techniques and 22% through point system techniques. The main categorization of these models concerns the parameters that are considered; there are methods based on quantitative parameters, methods based on qualitative parameters and methods that utilize both categories of parameters [24]. Over the years, there has been a shift from quantitative methods, which have their roots mainly in the USA and focus on flow and density, towards qualitative and mixed methods (combination of quantitative and qualitative parameters), which explore the characteristics of the built environment and consider the perceptions of the users. It is noted that the pedestrian LOS can be determined in various infrastructures, such as intersections and stairs, but the literature review focuses exclusively on sidewalks and pedestrian streets, due to the greater relevance to the subject and the objectives of the paper.

The first reference to the pedestrian LOS is that of Fruin [25], who sought to convey the concept of the motorized traffic LOS to the pedestrian traffic, considering that it should express the freedom of movement and the ability of pedestrians to walk with a desired speed and to overtake pedestrians moving at a lower speed. The logic of Fruin's methodology is being utilized and evolved by the Highway Capacity Manual. The methodologies proposed by the Highway Capacity Manual (2000 [26] and 2010 [21]) are considered the most widespread and widely accepted, despite the fact that there are studies that consider them unrepresentative and more specifically that they overestimate the pedestrian LOS [27,28].

2.1.1. Pedestrian LOS Based on Point System Techniques

The methodology of Linda Dixon [29] was one of the most important attempts to determine the pedestrian LOS, taking into account qualitative parameters and following the logic of scoring. Through this methodology, each infrastructure receives a grade on a scale from 1 to 21, with the grade corresponding to a LOS on a scale of A to F. The calculation of the grade is based on the infrastructure's performance in the following six categories of criteria: (a) pedestrian facility provided, (b) conflicts, (c) amenities, (d) motor vehicle LOS, (e) maintenance, and (f) transportation demand management. A similar logic for the determination of LOS is followed by the methodology of Jaskiewicz [30], which is well known as it considers some qualitative criteria that are not found in other methodologies: enclosure/definition, complexity of path network, building articulation, complexity of spaces, overhangs/awnings/varied roof lines, buffer, shade trees, transparency, and physical components/condition.

Gallin's methodology determines pedestrian LOS by examining whether an infrastructure is friendly to them [31]. The methodology is based on the performance in 11 qualitative and quantitative criteria, which are divided into three main categories: (a) design factors, (b) location factors, and (c) user factors. These criteria are weighted on the basis of their importance, after consultation with stakeholders and unlike the vast majority of LOS methodologies, Gallin's methodology expresses the final LOS into a five-level scale. The methodology proposed by Christopoulou and Pitsiava-Latinopoulou [28] also utilizes a combination of quantitative and qualitative parameters, which are determined after a review of previous methodologies and are divided into three main categories: (a) traffic factors, (b) geometry/environmental/sidewalk factors, and (c) pedestrian movement factors. Through a preliminary questionnaire survey, the assignment of weights in the various parameters is attempted, which, in combination with the evaluation of the infrastructure in relation to each parameter, leads to the total grade of the infrastructure, which is expressed in the widespread A-F scale.

Asadi-Shekari et al. [32,33] developed two different methodologies, which follow the same approach and more specifically the following steps: (a) review of various guidelines for pedestrian infrastructure design and recognition of important criteria for infrastructure evaluation, (b) weighting of each criterion based on whether the various guidelines delve into the specific criterion, (c) rating of infrastructure for each (qualitative and quantitative) criterion, (d) calculation of total infrastructure grade based on the individual grades and the weights of the criteria, and (e) grade expression in a LOS scale from A to F. It is therefore understood that the basis of this approach is the identification and examination of various guidelines, something that sets it apart from other methodological approaches. The two methodologies differ in the criteria chosen, as the first methodology [32] concerns the LOS provided to pedestrians with disabilities, while the second one [33] concerns the LOS of walking facilities on university campuses.

2.1.2. Pedestrian LOS Based on Statistical Modelling Techniques

One of the first and most commonly used models for determining pedestrian LOS is the one developed by Landis et al. [34], for which the multiple regression technique was used, utilizing 1250 observations from 75 pedestrians, who were invited to walk on the sidewalks of various geometric and operational characteristics and then to evaluate their experience in terms of comfort and safety, on an A–F scale. Their model includes statistically significant variables: (a) the width of the outside lane, (b) the width of shoulder, (c) the presence of parked vehicles along the road, (d) the distance between the edge of the pavement and the sidewalk, (e) the sidewalk width, (f) the average traffic volume in a 15-min period divided by the number of traffic lanes, and (g) the average speed of motorized traffic. A similar logic was followed by the methodology of Tan et al. [35], as it utilized regression techniques and quantitative parameters exclusively. The data for the development of the model came from 12 sidewalks with different characteristics in China and from the completion of 725 questionnaires by pedestrians. Their model is based on the following variables: (a) pedestrian volume, (b) bicycle volume, (c) motorized vehicles volume divided by the distance between the sidewalk and the nearest traffic lane, and (d) number of driveway accesses per meter.

Another popular methodology for determining pedestrian LOS is that developed by Jensen [36], which is based on responses from 407 people about the LOS they believe prevails in 56 videos taken in infrastructures in Denmark. Based on these data, a cumulative logistic regression model is being developed, with 13 independent variables and the most significant among them is the type and the width of the walking infrastructure, as well as the distance between the walking infrastructure and the nearest traffic lane.

Regression techniques are also being used by Frazila et al. [37], who formulate a methodology for pedestrian LOS from the point of view of visually impaired people, utilizing 30 interviews with visually impaired people, in order to identify the basic criteria that affect their perception of LOS, as well as the importance of each criterion. A recent research by Rodriguez-Valencia et al. [18] utilizes data from 30 different infrastructures in Bogota, Colombia, to explore the importance of integrating users' perceptions in determining QOS. More specifically, in the examined infrastructures, they carried out questionnaire surveys and at the same time, they collected data about geometric and functional characteristics of the infrastructures. The data collection is followed by the development of seven different ordinary least squares models, all of which have a common dependent variable (QOS), but a different combination of independent variables. They found that models that incorporate users' perceptions have better explanatory power and therefore conclude that their inclusion is crucial for developing more appropriate models than the more traditional ones that consider only the geometric and functional characteristics of the infrastructures.

In addition to the above methodologies, there is a significant amount of research efforts that utilize statistical modeling techniques with latent variables. One such effort is the research of Hidayat et al. [38], which is only based on questionnaire data and investigates the relationship between four latent variables, namely pedestrian traffic, pedestrian perceptions, behavior/attitudes and pedestrian LOS. The above methodology was evolved by the same research team, incorporating beyond pedestrian responses and field measurements and creating four latent variables: (a) comfort, (b) safety, (c) vendor's attraction and (d) vendor problem [39]. The methodology concludes with the formation of a model for the determination of pedestrian LOS, through linear regression, with the only statistically significant variables being the two latent variables (comfort and vendor problem), as well as the pedestrian volume and the number of pedestrians that interact with vendors.

The technique of structural equation models (SEM) is applied by the research by Said et al. [40], which collect data from university students and formulates two different SEMs, one for students who usually walk for their mandatory trips and one for those who usually walk for leisure. The theoretical model includes three latent variables that affect the pedestrian LOS, and the characteristics of the neighborhood, the width and quality of the sidewalk surface, and the diversity of activities. The results surprisingly show that the width and quality of the sidewalk surface do not have a statistically significant effect on the pedestrians' perceived LOS, in contrast to the diversity of activities and especially the characteristics of the neighborhood that have a significant impact on the LOS. Similar is the approach of Bivina and Parida [41], as they also rely solely on questionnaire data and use the technique of SEM. By collecting answers for 14 variables, they form the following four latent variables: (a) safety, (b) comfort/convenience, (c) security, and (d) mobility infrastructure, all of which are considered important in determining pedestrian LOS. A theoretical model that incorporates objective and subjective variables is sought to be developed by the research of Vallejo-Borda et al. [42], to determine the QOS and for this purpose they collect questionnaire data from 1056 pedestrians on 30 different sidewalks and analyzes them using the Ordered Probit Multiple Indicator and Multiple Cause (MIMIC) technique. The main conclusions of their research are that the prohibition of the use of the sidewalk by cyclists contributes to the significant improvement of the pedestrians' perceived QOS and that the inclusion of objective (i.e., directly measured in the field) and subjective (i.e., stated by users) variables in QOS models can provide reliable results.

2.1.3. Pedestrian LOS Based on Conjoint Analysis

Another technique that seems to be preferred for investigating pedestrian LOS is conjoint analysis, which was firstly applied in this field by Muraleetharan et al. [43]. The attributes that are being examined in their study are: (a) the width of the infrastructure and the separation from the motorized traffic, (b) the obstacles, (c) the pedestrian flow rate, and (d) the events with bicycles. The results provide evidence that the pedestrian flow rate is the most influential attribute, in addition to the presence of bicycles on sidewalks, which has an important negative impact on pedestrians' perceptions. A similar approach is followed by the research by Wicramasinghe and Dissanayake [44], which investigates the attributes: (a) width, (b) obstruction per 50-m, (c) pedestrian flow rate, and (d) percentage of handrails covered per 50 m (used as an indication of safe separation from motorized traffic). Recent efforts by a research team from the Indian Institute of Technology Kharagpur [45,46] provide a methodological framework for selecting appropriate attributes for examining and determining the pedestrian LOS, since they identify that a large number of attributes (variables) are suggested in the literature. The methodological approach starts with the review of the literature and the identification of 31 important attributes, and then, through experts' answers and the use of multi-criteria analysis techniques (e.g., Technique for Order Preference by Similarity to Ideal Solution-TOPSIS), the 16 most important attributes are selected for further investigation. The next stage of the methodological approach includes the users' opinions and their analysis through conjoint analysis. Through this process they come to the following important features: (a) sidewalk width, (b) aesthetics and quality of the sidewalk surface, (c) lateral separation from motorized traffic, (d) volume of motorized traffic, (e) degree of shade, (f) accessibility, (g) continuity, (h) degree of encroachment, and (i) pedestrian density.

2.2. Bicycle LOS

Numerous methodologies and studies have also been implemented for the bicycle LOS, with the efforts having been intensified in the last three decades [47]. These surveys have many features in common with those of pedestrians and can easily fall into the same categories. Regarding the evaluation of bicycle infrastructure, it is found that various terms are used (e.g., LOS, bicycle safety index rating, road condition index), which have similar meanings [48].

One of the most well-known and important methodologies for determining bicycle LOS is that of Botma [49], who introduced the concept of "hindrance", which is expressed by the frequency of events between bicycles (defines events as situations where one cyclist overtakes another or meets another). Botma's methodology has been widely accepted and adopted by the Highway Capacity Manual 2000 [26], but the Highway Capacity Manual 2010 [21] presents a different approach for the bicycle LOS, which primarily takes into account the nuisance that cyclists perceive from the adjacent motorized traffic. Thus, the attributes considered are related to the geometry of the road, the traffic volume, the speed of the vehicles, the percentage of heavy vehicles and the quality of the bicycle infrastructure surface. Research by Parks et al. [50] compared methodologies developed to determine bicycle LOS and concluded that the Highway Capacity Manual 2010 methodology is not sufficiently representative. A more recent methodology based on the concept of "hindrance" is that of Liang et al. [51], which focuses exclusively on overtakings, as the exclusive bike lanes in China are one-way and therefore no meetings between cyclists are observed. This methodology quantifies the hindrance based on the speed deviation of cyclists during an overtaking from their desired speed.

2.2.1. Bicycle LOS Based on Point System Techniques

The only methodology for determining the bicycle LOS is by exclusively using the point system approach by Dixon [29]. This research was also presented in Section 2.1.1, as one part concerns the pedestrian LOS and the other part concerns the bicycle LOS, but following the same approach for both of these parts. What separates the two parts of the research are the characteristics, i.e., the criteria, that are taken into account for the evaluation. In the case of bicycles the categories of criteria considered are the following: (a) bicycle facility provided, (b) conflicts, (c) speed difference between bicycles and motorized traffic, (d) motor vehicle LOS, (e) maintenance, and (f) transportation demand management.

In addition to Dixon's methodology, there is a small group of methodologies that incorporate elements of the point system approach and they appear to be quite popular, especially in the US. The first methodology to apply this approach was that of Davis [52], which aimed to formulate a simple mathematical formula for evaluating the level of safety provided to cyclists by an infrastructure. Some terms of the mathematical formula that were eventually developed are quantitative (daily traffic volume, number of lanes, speed limit, and outer lane width), while others are qualitative. The results deriving from the mathematical formula leads to the classification of the infrastructure into one of the four categories defined by the researcher, reflecting whether the infrastructure is safe for cyclists. Over the years, small variations of the abovementioned mathematical formula have emerged, with the aim of more accurately evaluating the infrastructure, and the most well-known modification is the one proposed by Epperson [53].

2.2.2. Bicycle LOS Based on Statistical Modelling Techniques

As in the case of pedestrian LOS, and in the case of bicycle LOS, the first attempt to use statistical modeling tools came from Landis et al. [54], who developed a linear regression model using responses from 150 people who were asked to ride a bike along 30 road sections with different geometric and functional characteristics and then to assign a grade on an A–F scale to each of the road sections. The research concludes that the two most decisive factors for the bicycle LOS are the striping of bike lanes and the quality of the road surface. The same approach, but for arterial roadways, was applied ten years later by Petritsch et al. [55]. One of the most well-known methodologies for determining the bicycle LOS is that of Jensen [36] (also known as the Danish method), which was also mentioned in Section 2.1.2, as he also proposes an equation for pedestrian LOS. Jensen collects responses about the LOS from people who watched recorded videos and then develops a cumulative logistic regression model, which includes 14 variables, with the most significant being the width of the bicycle lane and the distance of the bicycles from the motorized traffic and pedestrians. The answers of 198 cyclists, regarding the LOS they perceive, are utilized by the research of Kang and Lee [56]. The ordered probit regression model they developed includes, as statistically significant variables, the width of the infrastructure, the type of infrastructure (whether it is used for leisure or not), the number of pedestrians and cyclists a cyclist encounters in 15 min and the number of lanes on roads intersecting the bicycle infrastructure. Foster et al. [57] followed the approach of the Danish method, i.e., they use the same data collection and analysis techniques, applying them to protected bike lanes in the USA. They develop three different models, where the first two utilize easily available data, while the third model uses a wider range of variables to investigate whether the extra effort to gather more data has a significant positive impact on the quality of the model. Their results lead to the selection of one of the two simple models.

Significant efforts for determining bicycle LOS have been made and published by a research team of the National Institute of Technology Rourkela, India. In their first attempt [58], they used data about infrastructure characteristics and evaluations made by 141 respondents for 74 road segments and they combined machine learning (random forests) and statistical analysis (ordered probit) tools for developing a mathematical formula that determines the LOS. Their following research efforts [59,60] were based on data from the same 74 road segments and techniques that included exclusively machine learning algorithms (functional networks, Levenberg–Marquardt neural network).

The bicycle LOS, through the investigation of the users' opinion, is examined by the research of Bai et al. [61], which collected responses from 471 traditional bicycle users, 518 electric bicycle users and 589 electric scooter users and analyzed them by developing four ordered probit models, one for each user category and one aggregated. A main conclusion drawn from their analysis is that users of traditional bicycles are more likely to perceive higher LOS compared to the other two categories of users, while they recognize, as important parameters, the following: (a) the width of the bicycle lane, (b) the existence of physical separation between motorized, pedestrian and bicycle lanes, (c) the volume of two-wheeled volumes, (d) the slope, (e) the roadside land use, (f) the roadside access points and (g) the age of cyclists. Ordered probit models seem to be the most commonly used statistical modeling technique for examining bicycle LOS, which is certainly due to the ordinal nature of LOS. This technique is also used by two more recent studies, utilizing data from users in India [62] and in Colombia [63].

In addition to the abovementioned studies that examine the LOS, of particular interest are two recent studies where the first [64] concerns the perceived level of comfort (LOC) of cyclists and the second [65] the QOS. In the case of the first study [64], an online questionnaire survey was utilized, which asked participants to express, on a 10-point scale, whether they consider comfort as the environment shown in 18 three-dimensionally rendered images, which had differences concerning the traffic volume, the pavement markings and the traffic signs. Through statistical analysis (repeated-measures ANOVA tests), they conclude that the most important factor that degrades cyclists' LOC is the truck traffic in the adjacent lane. Regarding the second study that concerns the QOS [65], it uses structural equation models, based on cyclists' responses collected at 16 sites with different characteristics, in order to investigate the impact of cyclists' attitudes and perceptions on determining QOS. The theoretical model they finally developed included four latent variables (signage, interferences, convenience, and attitudes) and three directly measurable variables (paving, enjoyment, and perceived QOS). Their analysis concludes that three variables have a direct impact on QOS, the signage, the enjoyment and the paving, with the most important being the signage.

2.3. Pedestrians-Cyclists Shared Space LOS

Botma's research [49], presented in Section 2.2, in addition to the methodology it proposes for bicycle LOS, also proposes a methodology for determining the LOS in pedestrians–cyclists shared infrastructure and it is considered very important, as it was the first to be proposed for the infrastructure of this type and was the basis for subsequent ones. As in the case of bicycle LOS, his methodology is based on the concept of "hindrance" and consequently on the frequency of events between the users of the infrastructure. It is obvious that, in the case of pedestrians–cyclists shared infrastructures, the categorization of events is not only related to the angle (i.e., overtaking or meeting), but also to the type of users who interact (e.g., cyclist with cyclist and cyclist with pedestrian). The next attempt to formulate an appropriate methodology for determining LOS in pedestrians–cyclists shared infrastructure was made several years later by Hummer et al. [66], who used Botma's methodology as a basis and tried to improve some of its points (e.g., calibration and validation in conditions that have differences from the conditions in the Netherlands, inclusion of additional types of events, examination of various infrastructure widths). The process of developing their methodology includes an extensive collection of field data from a number of infrastructures in various US States, as well as a questionnaire survey addressed to infrastructure users. Their methodology concludes with the formulation of a statistical model that includes, as independent variables, the following: (a) weighted events per minute, (b) reciprocal of the width, (c) existence of a centerline or not (binary variable), and (d) an adjustment factor to take into account delayed overtakings/passings.

A following methodology for determining LOS in pedestrians–cyclists shared use infrastructure was that of Petritsch et al. [67], which follows the statistical modeling approach using data from a questionnaire survey and measurements of geometric and functional characteristics of infrastructures. Using the Pearson correlation coefficient, the variables that affect respondents' perceptions are investigated and then the variables that are highly correlated with other independent variables are eliminated, assisting the researchers to select a regression model that includes, as independent variables, only the average speed of the motorized traffic and the width of separation between shared infrastructure and motorized traffic. The use of statistical modeling techniques (ordered probit model) is followed by the research by Kang et al. [68] for the identification of LOS on sidewalks that are also used by cyclists. Their methodology is based only on pedestrians' perceptions and their model shows that their perceived LOS is mostly affected by the pedestrian flow rate, but also by the sidewalk width, the type of separation from the roadway environment, the presence of parking and businesses along the sidewalk, the bicycle flow rate, the cyclists' speed, the weather conditions, the time of the day and the age of the pedestrians. A similar approach was followed by Nikiforiadis and Basbas [69], who developed an ordinal regression model and highlighted the importance of correctly allocating the sidewalk or pedestrian street space between pedestrians and cyclists. A more recent study from the same research team develops a methodology for the assessment of pedestrians–cyclists shared infrastructure, using Botma's hindrance concept as a basis [70]. The novelty of this methodology is the application of regression tree models for predicting events' frequency, as well as the application of multicriteria techniques for assigning weights in each type of event based on their negative impact on pedestrians' and cyclists' perceptions. The most recent research aiming to determine the LOS in pedestrians–cyclists shared infrastructure is that of Wang et al. [71], which is also focused on the events between infrastructure users.

3. Materials and Methods

3.1. Methodology

Since the aim of this paper is to provide a fruitful discussion about the LOS in pedestrians–cyclists shared spaces and the various methodologies that exist, the first step of the methodology was to make an extended literature review concerning proposed methodologies for pedestrian LOS, bicycle LOS and shared space LOS. To facilitate the discussion around the various methodologies, it was considered appropriate to select and to apply some of them in two pedestrians–cyclists shared spaces with different characteristics (both operational and geometrical). The criteria for the methodologies' selection were the following: (a) popularity, (b) ease of use, (c) inclusion of both quantitative and qualitative methodologies, and (d) inclusion of methodologies that are based on pedestrians' perspective, on cyclists' perspective and on both users' perspective.

For the application of the methodologies and the calculation of LOS, field measurements were carried out in the two shared spaces. The field measurements were conducted during hours, which were assumed "close" to the peak-hour of each street, since these conditions were considered appropriate for the LOS calculation. Moreover, a short questionnaire was addressed to pedestrians and cyclists using the two-shared spaces, targeting the identification of a tendency about the perceived LOS and to compare it with the calculated LOS from the various methodologies.

The combination of the literature review and the results from the methodologies' application in the two shared spaces leads to a critical discussion about advantages and disadvantages of the different categories of methodologies. Furthermore, it assists in the derivation of suggestions for future research and practice.

3.2. Study Area

The study area of the current research is located in a typical medium-sized city of Northern Greece, Serres, the second largest city in terms of population and economic growth in the Region of Central Macedonia. The latest census (2011) carried out by the Hellenic Statistical Authority [72], places Serres as 10th among Greek cities according to their population, with a total of 76,817 inhabitants, 52,287 of which in the core Municipality. After the implementation of "Kallikratis" plan, which reformed the Greek administrative system, the Municipality of Serres consists of six units and extends over an area of 601.5 km^2. Being the capital of the Serres Prefecture, it is a pole of attraction for the whole Regional Unit and a significant cultural, commercial and industrial center.

According to the latest Urban Mobility Study (UMS), conducted in 2015 [73] and the updated measurements realized within the recent study of Sustainable Urban Mobility Plan—SUMP in 2019 [74], the Central Business District (CBD) attracts over 50% of the daily trips with the main trip purpose commuting to work, thus being a mixed land use area under intense environmental pressure, especially during peak hours. Public Transport patronage is low, despite the adequate spatial coverage and citizens are rather car-addicts, using private cars even for short-distance trips, while the average trip length in the city of Serres is approximately 1.5 km.

In an effort to mitigate impacts of motorized transport dominance, local authorities, which is mainly the Municipality of Serres, has undertaken a Sustainable Urban Development Strategy, in line with European guidelines, achieving receipt of a considerable relevant European and national funding. The last supported a consistent approach of upgrading the public space in favor of pedestrians, which was followed throughout the last 25 years, leading to the implementation of an extensive footpath network mainly in the central area of the city of Serres consisting of 41 footpaths and to a totally new "scenic" in the city center [75]. In fact, during the last two decades, the city has met a range of interventions, as a result of several individual projects or dictated by strategical studies like UMS in 2015. Towards this direction, several research programs and relevant studies were conducted, feeding with their deliverables, the city's inventory with mobility management suggestions, active travel audits and a local plan for bicycle use enhancement [76]. The most recent Sustainable Urban Mobility Plan of the city included a methodological approach comprising a comprehensive "before and after" study that considers the impact of traffic calming measures on traffic flows, travel speed, traffic accidents, fuel consumption, GHG and air pollutant emissions, while it also considers the acceptance of the examined interventions, as perceived by the locals [77].

In this framework, a dense network of pedestrianized streets was gradually created, cycling paths were introduced with the aim to create a respective functional network soon, a series of traffic calming measures was implemented and large construction projects of urban reform and bioclimatic upgrade have really improved the city's image and living conditions. In addition, walking encouraging equipment was installed, as well as facilities to promote bicycle use like bicycle parking stands and a bike-sharing system introduced in June 2020, providing evidence of the city's commitment towards active travelling. The above was also accompanied by soft measures that were implemented in an attempt to discourage private car use and promote active alternatives modes, walking and cycling, like local campaigns. In early 2020, the SUMP of Serres was finalized, enriching the city's inventory with a detailed road map for the next actions towards sustainable mobility in Serres, a major intervention being the expansion of the cycling infrastructure, uniting existing paths into a long and continuous network, as is presented in Figure 1.

Figure 1. Cycling network of Serres (Cartographic background: [78]).

3.3. Data Collection

Among the different interventions implemented in the city of Serres, this research focuses on a major intervention in the heart of the city, which is Karamanli street reform and the respective reform of one of the local streets that intersects with it, Dimosthenous Floria Street (see Figure 2).

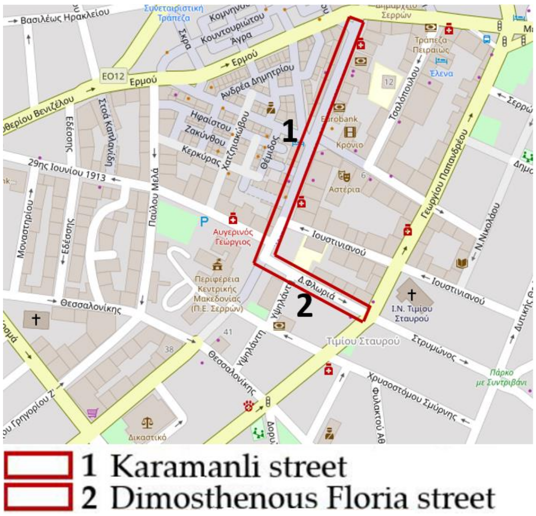

Figure 2. Study area includes all along Karamanli street and its vertical intersection with Dimosthenous Floria street (Cartographic background: [78]).

The reform includes the pedestrianization of Karamanli street with a cycling path all along the renovated part of the street, as well as a part with traffic calming measures at its southern part and the urban reform in Dimosthenous Floria Street with pavement improvements and a cycling path on the same level with the one side pavement. The choice of the streets to be studied was based on the co-existence of walking and cycling infrastructure at a shared level, and the fact that they are located in the city center and were part of relevant funding for urban upgrade. Admittedly, between the two chosen streets, the differences are obvious: first, their geometric characteristics differ by far, with Karamanli street having been renovated at a length of 350 m, whereas Dimosthenous Floria Street is a street of only 120 m length, fully reformed. Administratively, Karamanli street is an urban artery. It is pedestrianized for 230 m and then it has traffic calming infrastructure in place. Dimosthenous Floria Street is a local street with motorized traffic and a cycling path at the same level with the pavement at one side of the street. Dimosthenous Floria Street is a "traffic outlet" for the volume inserting Karamanli Street forms its former intersection with Ioustinianou Street. Figures 3 and 4 present snapshots from the two streets.

Figure 3. Karamanli shared space street.

Figure 4. Dimosthenous Floria shared space street.

For the calculation of LOS in the two shared space streets, a series of field measurements were carried out. Through the measurements, the geometrical and operational characteristics of the two shared space streets were captured (see Table 1). It is noted that the measurements in Dimosthenou Floria street concern only the space that it is allocated for pedestrians and bicycles and not the one that it is allocated to motorized vehicles. It is also highlighted that the operational characteristics were measured during hours that were assumed "close" to the peak-hour of each street. A situation "close" to the peak-hour was considered appropriate for the LOS calculation with the various methodologies.

Table 1. Geometrical and operational characteristics of the two shared space streets.

Characteristic	Karamanli Street	Dimosthenous Floria Street
Total width [m]	9.70	4.75
Effective width [m]	5.9	0.7
Bicycle lane width [m]	2.0	2.0
Pedestrian volume [ped/h]	424	229
Bicycle volume [bic/h]	53	29
Pedestrian flow rate [ped/min/m]	0.7300	0.8052
Bicycle flow rate [bic/min/m]	0.0913	0.1020
Average pedestrian speed [m/s]	1.18	1.36
Average bicycle speed [m/s]	2.45	2.96

Additionally, 155 questionnaires were filled in person by randomly selected pedestrians and cyclists in the two streets, between 15th and 19th of February 2020 (that is before the appearance of the COVID-19 pandemic in Greece). More specifically, 50 questionnaires by pedestrians and 37 by cyclists were filled in Karamanli Street, while 40 questionnaires by pedestrians and 28 questionnaires by cyclists were filled in Dimosthenous Floria Street. The sample can be considered small, but its aim was not to feed a statistical analysis, but only to reveal a tendency about pedestrians' and cyclists' perceived LOS in the two shared space streets. Table 2 presents a short description of the survey participants' profile.

Table 2. Respondents' demographic and mobility profile.

Variable	Karamanli Street		Dimosthenous Floria Street	
	Pedestrians	Cyclists	Pedestrians	Cyclists
	(n = 50)	(n = 37)	(n = 40)	(n = 28)
Age	18–24: 20% 25–39: 30% 40–54: 22% 55–64: 14% ≥65: 14%	18–24: 29.7% 25–39: 32.4% 40–54: 16.2% 55–64: 16.2% ≥65: 5.4%	18–24: 40% 25–39: 22.5% 40–54: 22.5% 55–64: 12.5% ≥65: 2.5%	18–24: 32.1% 25–39: 28.6% 40–54: 25% 55–64: 7.1% ≥65: 7.1%
Gender	Male: 48% Female: 52%	Male: 51.4% Female: 48.6%	Male: 55% Female: 45%	Male: 60.7% Female: 39.3%
Frequency of using specific street	Daily: 44% 2–3 times/week: 36% 1 time/week: 8% Rarely: 12%	Daily: 51.4% 2–3 times/week: 37.8% 1 time/week: 5.4% Rarely: 5.4%	Daily: 65% 2–3 times/week: 30% 1 time/week: 5% Rarely: 0	Daily: 21.4% 2–3 times/week: 25% 1 time/week: 17.9% Rarely: 35.7%
Frequency of using shared space streets	Daily: 48% 2–3 times/week: 26% 1 time/week: 6% Rarely: 20%	Daily: 51.4% 2–3 times/week: 37.8% 1 time/week: 2.7% Rarely: 8.1%	Daily: 77.5% 2–3 times/week: 20% 1 time/week: 2.5% Rarely: 0	Daily: 28.6% 2–3 times/week: 32.1% 1 time/week: 14.3% Rarely: 25%
Pedestrian's experience of collision with bicycle	Yes: 26% No: 74%	-	Yes: 25% No: 75%	-
Cyclist's experience of collision with pedestrian	-	Yes: 24.3% No: 75.7%	-	Yes: 21.4% No: 78.6%
Pedestrian's experience of "near-collision" with bicycle	Yes: 60% No: 40%	-	Yes: 67.5% No: 32.5%	-
Cyclist's experience of "near-collision" with pedestrian	-	Yes: 67.6% No: 32.4%	-	Yes: 64.3% No: 35.7%

4. Results

Based on the criteria that were presented in the Section 3.1, the following methodologies were selected and applied to the two shared space streets:

- Highway Capacity Manual 2010 [21]: From this manual both the methodology presented in Chapter 17 and the methodology presented in Chapter 23 were applied. The methodology in Chapter 17 concerns pedestrian LOS in urban street segments, while the methodology in Chapter 23 concerns off-street pedestrian and bicycle facilities and a LOS value can be calculated from both pedestrians' and cyclists' perspective. The methodologies from both chapters were selected for the comparison since the two examined shared infrastructures are urban street segments, but at the same time the interaction of active mode users with the motorized traffic is limited.
- Botma, 1995 [49]: Through this methodology, which is considered one of the most important in the field, a single value is calculated for the shared infrastructure.
- Tan et al., 2007 [35]: This methodology, which proposes one of the most easily used models, concerns the pedestrian LOS in sidewalks as the Chapter 17 of the Highway Capacity Manual.
- Nikiforiadis et al., 2020 [70]: This methodology is suitable for pedestrians-cyclists shared sidewalks and pedestrian streets and produces a single value of LOS for the infrastructure.
- Dixon, 1996 [29]: This is one of the first qualitative attempts that uses the point-system approach and proposes a methodology both for pedestrians' and cyclists' LOS.

- Jaskiewicz, 2000 [30]: Through this methodology only pedestrians' LOS can be calculated, using a set of qualitative parameters that are significantly different compared to those proposed in other similar methodologies.
- Gallin, 2001 [31]: This methodology belongs to the same "family" with the two abovementioned methodologies and it can calculate a LOS only for the pedestrians, through an easily applicable procedure.
- Frazila et al., 2019 [37]: This methodology follows the perspective of visual impairment persons using qualitative parameters. However, it does not apply the point-system approach, but a statistical modelling approach.

It is noted that, for computing LOS with the qualitative methodologies, the two examined shared infrastructures were evaluated per parameter from an experienced transport engineer with great familiarity with the transport infrastructure in the city of Serres. The subjective judgment for the evaluation of infrastructure with qualitative methodologies is inevitable and it is assumed that their use by engineers with experience in both the subject and the specific infrastructure can mitigate any failures.

In the following tables, along with the computed LOS values with the various methodologies, the perceived LOS of pedestrians and cyclists is presented. The perceived LOS was identified as the closest LOS value to the average score of the users, where: (a) LOS A equals to 5, (b) LOS B equals to 4, (c) LOS C equals to 3, (d) LOS D equals to 2, (e) LOS E equals to 1, and (f) LOS F equals to 0. More specifically, the average score of pedestrians for the Karamanli shared space street was 3.68 (corresponds to LOS B) and the average score of cyclists for the same infrastructure was 3.70 (also corresponds to LOS B). Regarding the Dimosthenous Floria shared space street, the average score of pedestrians was 2.70 (corresponds to LOS C) and the average score of cyclists 3.18 (also corresponds to LOS C).

Tables 3 and 4 present the results for the Karamanli and the Dimosthenous Floria pedestrians–cyclists shared infrastructures, respectively. It is highlighted that, for the methodologies that produce a single LOS value for the infrastructure, this value has been filled both in pedestrians' and cyclists' columns. Regarding the quantitative methodologies, it is obvious that the two methodologies that produce results only for pedestrians overestimate the performance of both infrastructures, due to the fact that in these methodologies LOS is affected mostly by the adjacent motorized traffic, but in the case of the two examined infrastructures, the interaction with motorized traffic is limited. Additionally, it can be observed that the results of the quantitative methodologies are very similar in both infrastructures. This similarity is, to a large extent, attributed to the similar pedestrian and bicycle flow rates, since the infrastructure with the higher volumes is much wider. The only quantitative methodology that produces different results in the two infrastructures is that of Botma [49], but it seems that this difference does not correspond to what users perceive (i.e., Botma's methodology produces higher LOS, where users perceive lower LOS). On the whole, it is understood that the two quantitative methodologies that do not produce extreme values (at either end of the A-F scale) and converge more with users' perceived LOS are that of Botma [49] and Nikiforiadis et al. [70]. These two methodologies have been developed in a way that makes them capable of specifically assessing pedestrians–cyclists shared infrastructures, such as those that are examined in the present paper.

Regarding the qualitative methodologies, it seems that they manage to provide LOS values closer to the users' perception, as compared with the quantitative methodologies, while they also largely agree with users that the Karamanli shared infrastructure provides a higher LOS from the Dimosthenous Floria infrastructure. It is also highlighted that the qualitative methodologies approach users' perceived LOS, despite the fact that they examine the infrastructures as if they were single use targeted infrastructures, either for pedestrians or cyclists. The difference in the results between the qualitative methodologies (i.e., Dixons' methodology produces a significantly lower LOS for both infrastructures comparing with Jaskiewicz's and Gallin's methodology) is to a large extent attributed to the level of detail of the parameters under consideration.

Table 3. Results from the various methodologies and users' perceptions for Karamanli pedestrians–cyclists shared infrastructure.

Category of Methodologies	Methodologies	LOS	
		Pedestrians	**Cyclists**
Quantitative methodologies	Highway Capacity Manual 2010 [21] Chapter 17	A	-
	Highway Capacity Manual 2010 [21] Chapter 23	A	E
	Botma, 1995 [49]	C	C
	Tan et al., 2007 [35]	A	-
	Nikiforiadis et al., 2020 [70]	D	D
Qualitative methodologies	Dixon, 1996 [29]	D	D
	Jaskiewicz, 2000 [30]	A	-
	Gallin, 2001 [31]	A	-
	Frazila et al., 2019 [37]	C	-
Users' perception		B	B

Table 4. Results from the various methodologies and users' perceptions for Dimosthenous Floria pedestrians-cyclists shared infrastructure.

Category of Methodologies	Methodologies	LOS	
		Pedestrians	**Cyclists**
Quantitative methodologies	Highway Capacity Manual 2010 [21] Chapter 17	A	-
	Highway Capacity Manual 2010 [21] Chapter 23	A	E
	Botma, 1995 [49]	B	B
	Tan et al., 2007 [35]	A	-
	Nikiforiadis et al., 2020 [70]	D	D
Qualitative methodologies	Dixon, 1996 [29]	D	D
	Jaskiewicz, 2000 [30]	B	-
	Gallin, 2001 [31]	B	-
	Frazila et al., 2019 [37]	C	-
Users' perception		C	C

5. Discussion

As has already been stated, the present paper intends to provide directions for future research in the field of pedestrian and cyclist LOSs, as well as guidance to practitioners who have to select from a plethora of available methodologies the most appropriate one for assessing the infrastructure under their responsibility. The directions for future research are mainly derived from critically discussing the set of the relevant methodologies presented in the literature review, while the guidance to the practitioners is to a large extent derived from the application of specific methodologies in two pedestrians–cyclists shared infrastructures in a medium-sized city in Greece.

Based on the review of the various methodologies and studies on pedestrian and bicycle LOS, the following main conclusions are drawn:

- There are many studies that draw useful conclusions about the characteristics (variables) that affect LOS, but the studies that result in an easy-to-use (including the data collection process) mathematical model that can constitute a useful tool for practitioners are limited.
- The inclusion of quantitative and qualitative characteristics is what provides the more accurate results as it can describe, in a more holistic way, the experience of the pedestrian or cyclist. However, in the vast majority of cases, qualitative characteristics involve the subjectivity of the researcher or practitioner. Therefore, it is necessary to have a way of quantifying these characteristics as well. For instance, two commonly

used characteristics are lighting and signage, but when can lighting and signage be considered to be in good or even acceptable levels?

- According to some studies, the inclusion of variables derived from user responses (e.g., perceived safety, perceived comfort) contributes significantly to the development of more representative methodologies. This finding is considered logical in advance, as users' responses to specific qualitative characteristics of the infrastructure also show a trend for their overall view of the infrastructure. Especially when these characteristics concern the level of comfort and the level of safety, which are main components of the evaluation metrics of pedestrian and bicycle infrastructure. However, the inclusion of these variables does not provide substantial guidance to the practitioners who will be called upon to design a new infrastructure, as the following questions remain without an objective answer: (a) How should I design or manage an infrastructure to be safe? (b) How should I design or manage an infrastructure to be comfortable? In addition, the need for input from user whenever the LOS (or QOS) needs to be determined negates the usefulness of methodologies, as in this case users could be asked directly about the LOS (or QOS) they perceive.

In conclusion, an aim of future research should be to describe as satisfactorily as possible the perceptions of pedestrians and cyclists, using objective variables, which will be part of an easily used (or relatively easily used, depending on the possibilities of data collection and the desired accuracy of the results) mathematical model.

Regarding the application of methodologies in the two shared infrastructures in the city of Serres, the main conclusion that can be drawn is that "one size (methodology) does not fit all". The meaning of this phrase is two-folded and concerns both the type of infrastructure and the local context. The application in the case of Serres shows that methodologies, which have been developed for assessing infrastructures with different characteristics from the one that they are applied cannot provide accurate results. For instance, in this paper, the pedestrian LOS methodologies that mainly take into account the negative impact of the adjacent motorized traffic do not achieve to approach the perceptions of the users and overestimate the performance of the infrastructure. Moreover, the infrastructures' characteristics can vary significantly among the different countries. For example, pedestrians–cyclists' shared paths in the U.S.A. are mostly outside the built environment and they are mainly used for recreational purposes, while the co-existence of pedestrians and cyclists in Europe in many cases takes place on sidewalks and pedestrian streets. An additional conclusion from the application of the methodologies is that, when assessing a pedestrian, cyclists or shared infrastructure, the triangulation of the results, using both an appropriate quantitative and qualitative methodology, is advisable since they can cover different aspects of the infrastructure. However, relying only on qualitative methodologies is not suggested, despite being found to provide relatively accurate results, because they are subjective from their nature and the quality of the results is highly affected by the estimation and therefore the experience of the practitioner.

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