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Algorithm for defining bicycle infrastructures on existing city roads

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Professional paper

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Algorithm for defining bicycle infrastructures on existing city roads

The lack of space within the existing road profile has led to a lack of cycling infrastructure and the increasing mixing of cycling and motor vehicle traffic. A growing problem in modern cities is traffic due to the large number of motor vehicles. From the perspective of health, ecology and reducing traffic congestion, it is necessary to find a sustainable solution for traffic management in large cities.This paper presents an algorithm for defining bicycle paths in urban conditions. After the defined algorithm, the example of the city of Niš was taken as a check of the entire algorithm and its principle for further use. All types of traffic roads were analyzed, i.e., main, access, and collecting roads. The algorithm is divided into specific parts to include all the necessary elements for planning the bicycle path, both in the geometry design and in terms of the functionality of the bicycle path itself. Based on everything presented, the authors concluded that the algorithm includes all the necessary elements and can be applied in most cities, both here and in Europe.

Key words:
city roads, bicycle infrastructure, road geometry, road design

Stručni rad

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Algoritam za definiranje biciklističke infrastrukture na postojećim gradskim prometnicama

Nedostatak prostora unutar postojećega profila ceste uzrokovao je nedostatak biciklističke infrastrukture i sve češće miješanje biciklističkoga prometa i prometa motornih vozila. Promet je sve veći problem u suvremenim gradovima zbog velikoga broja motornih vozila. Sa stajališta zdravlja, ekologije i smanjenja prometnih gužva treba pronaći održivo rješenje za upravljanje prometom u velikim gradovima. U radu je prikazan algoritma za definiranje biciklističkih prometnica u gradskim uvjetima. Nakon definiranoga algoritma na primjeru je grada Niša provjeren cjelokupni algoritam i njegov principa za daljnju uporabu. Za analizu su uzeti svi tipovi prometnica, odnosno analizirane su magistralne, pristupne i sabirne ceste. Algoritam je podijeljen u određene dijelove kako bi obuhvatio sve potrebne elemente za planiranje biciklističke prometnice, kako u tlocrtnom i visinskom prikazu te poprečnom presjeku, tako i u pogledu funkcionalnosti biciklističke prometnice. Na temelju izloženoga autori su zaključili da algoritam obuhvaća sve elemente koji su potrebni i da se može primijeniti u većini gradovima kod nas i u Europi.

Ključne riječi:
gradske prometnice, biciklistička infrastruktura, geometrija prometnice, projektiranje ceste

1. Introduction

Environmental protection and methods for solving increasingly large ecological problems are becoming very current and challenging topics in the field of technical sciences. Air pollution has become a problem throughout Europe. One possible solution is to strive for environmentally sustainable forms of transportation, as well as the reduction of the number of vehicles that use fossil fuels. The authors of the paper [1] propose optimizing the approach to designing bicycle infrastructure to increase environmental, health and time benefits. A mathematical model that defines the problems and limitations in designing bicycle infrastructure has been created. The model takes into account pollution emissions, cyclist health and interaction with other types of traffic. The results show that by properly and optimally deploying cycling infrastructure, it is possible to reduce the negative impacts of traffic and improve public health. A significant indirect step was taken during the Covid pandemic when the use of bicycles as a means of transportation was emphasized. A positive trend towards increasing the number of bicycle users and bicycle infrastructure has been observed. The Covid-19 pandemic has spurred the development of bicycle infrastructure in urban areas. The authors of the paper [2] propose a methodology that identifies/finds possible locations for improving bicycle infrastructure in Paris. Two methods were applied. The first one finds possible locations at the street level, while the other analyzes possibilities at the city level, taking into account important destinations. By analyzing the research results, the authors confirmed that the developed methodology provides reliable results from the perspective of assessing bicycle infrastructure and suitability for cycling. One of the newly emerging problems is the partially or completely underdeveloped bicycle infrastructure. The authors of the paper [3] analyze the behavior of cyclists when choosing the optimal route within the existing cycling infrastructure in the city of Waterloo, Canada. To assess the key factors in choosing the optimal route, two logit analyses and data on existing routes were used, such as terrain slope, existence of bicycle paths, road length and car speed. The operating models [3] are based on GPS data which can be very useful when planning and determining the location of bicycle infrastructure. In the paper [4], the authors deal with determining the best route for the construction of bicycle infrastructure in the city of Shiraz, Iran. An analytical hierarchy process was applied to rank and evaluate the routes, and three criteria were used: attractiveness, safety and mobility. The results show that the most important factors are the slope and speed limit. The most important criteria are safety (75 %), attractiveness (15 %), while mobility plays a very small role in choosing the location of bicycle infrastructure. The design and optimal location of bicycle infrastructure was researched on a pilot network by the authors of the paper [5]. The main goal of the author's research was to find a way to optimize bicycle infrastructure in urban areas, while minimizing the costs of building bicycle infrastructure and the costs of its users. A mathematical model was applied to determine the optimal type of bicycle infrastructure. This model is based on investment and user costs. A mathematical model based on the efficient design of bicycle infrastructure, in order to increase user safety, was applied in the paper [6]. The authors of the paper investigate how, using an algorithm, to design an efficient bicycle network that would increase cyclist safety and reduce the distance to be covered in the city of Malaga. Data from the analysis of geometric restrictions, such as the widths of pedestrian paths, traffic lanes, dividing strips, etc., are used as key parameters of the algorithm. An analysis of the literature has identified a trend towards introducing and optimizing bicycle infrastructure within existing road profiles [7]. In addition to design and placement, special attention was paid to connecting key points of an urban area, which also increases the mobility of the city. The authors of the paper [8] investigate how user-friendly the bicycle infrastructure really is, analyzing how much cyclists have to deviate from the shortest route due to poor path connectivity. Using GPS data from different urban environments, the authors discovered large differences in the quality of cities' bicycle networks. Poorly planned routes have been shown to force cyclists onto longer and less practical routes, which reduces the attractiveness of cycling as a form of transport. The paper [9] analyzes the functionality of the bicycle network in Montreal, with an emphasis on the connectivity and directness of routes. The authors of the paper [9] warn that the length of the paths alone is not enough if they are not well connected and adapted to the needs of cyclists. Many cyclists avoid existing paths due to poor connectivity, which points to shortcomings in planning. Better network integration and optimization can significantly improve cycling as a sustainable mode of transport in cities. In addition to good connectivity, the safety of cyclists, as well as other road users, must be a priority. The authors of the paper [10] use a bicycle simulator to analyze different traffic conditions to investigate how the design of bicycle infrastructure affects the safety of cyclists. The results show that more clearly separated bike lanes and better signalization can significantly reduce the risk of accidents. The study highlights the importance of simulations in testing safety solutions and offers recommendations for improving bicycle infrastructure in cities. This paper presents an algorithm for finding and placing bicycle infrastructure in the existing urban road profile. The aforementioned algorithm reaches an optimal solution and suggests the location of bicycle infrastructure depending on the rank of the city road, the geometry of the cross-section, the location of economic centers, recreational and cultural spaces, as well as many other characteristics of a modern city that play an important role in the design of transport infrastructure.

2. General terms

2.1. Bicycle infrastructure

In order to better define, analyze and solve problems of bicycle infrastructure in urban areas, it is necessary to define general terms of bicycle infrastructure. The term bicycle infrastructure includes the area intended for cycling, signage and space for storing bicycles. While riding, a cyclist is a person who maintains balance, a driver and a worker at the same time. A bicycle is an unsafe, but also very practical means of transportation. Cycling is classified as slow traffic, but in cities it can be the fastest form of transportation [11]. The technical forms of bicycle infrastructure, discussed in this paper, can be divided into:

- bicycle routes,
- bicycle paths,
- bicycle lanes,
- cyclists on the pavement.

Bicycle route is a road that is properly marked with horizontal and vertical traffic signs and is primarily intended for bicycle traffic. Under certain road traffic rules, in certain places it can be used as a mixed or shared area for cyclists and other users. The bicycle route is mainly used for sections outside urban areas [11].

Bicycle path is a part of the traffic surface that is not at the same level as the roadway or is separated from it in some other way, and is intended for the movement of bicycles and motorized bicycles. In populated areas, the bicycle path can be separated from the roadway only by a curb, while the service area outside the settlement is separated by a steel protective fence [11].

Bicycle lane is a longitudinal section of the roadway marked with a dividing line and intended for the movement of bicycles and motorized bicycles. When it comes to the bicycle lane, it is not different in elevation compared to the roadway and its surface is red for safety reasons [11].

Cyclists on the pavement are the concepts of guiding bicycle traffic on the pavement together with motor vehicles, using proper traffic signals. This concept is applied in urban areas when, for spatial reasons, it is not possible to create an independent cycling area. It is also important to note that roads with lower motor vehicle traffic frequency are more suitable for applying this method of bicycle traffic management [11]. Table 1 presents the key criteria for designing bicycle paths in urban areas. Limit values for daily traffic load of motor vehicles Q_{dn}, peak hourly load Q_h and the peak hourly cyclist load Q_{bh} influence the correct choice of the type of bicycle infrastructure. In addition to the above parameters, from a safety perspective, the maximum speed of motor vehicles shown in Table 1 plays a very important role.

The geometry of the path and the boundary values of geometric elements represent a very important part of the analysis and determination of the position of the future cycling route. Under this term, we distinguish between horizontal and vertical geometric elements of the path. Horizontal geometric elements of the path consist of road lines and horizontal curves at the intersections of road lines, or horizontal curves. From a safety perspective, minimum values for horizontal curves of the cycling surface have been defined depending on the speed of the cyclist. These values are shown in Table 1 and represent the values of the minimum radii of horizontal curves.

Vertical geometric elements consist of road elevation and vertical curves at the points of elevation breaks. For cycling surfaces, if the change in longitudinal slope is less than 5 %, vertical curvature of the elevation is not necessary, but it is recommended that the curvature radius be greater than 4 m. If the change in the slope of the elevation is greater than 5 %,

Table 1. Requirements for designing bicycle paths [12]

Criterion	Cyclists share the pavement	Bicycle lanes (t_b)	Bicycle paths (b_s)
Type	Cyclists ride on the roadway with motor vehicles	One-way, along the right edge of the roadway	Two-way, physically separated from the roadway
Daily load (Q_{dn})	≤ 1500 vehicles/day	1500 – 4000 vehicles/day	> 4000 vehicles/day
Peak hourly load (Q_h)	≤ 150 vehicles/hour	150 – 400 vehicles/hour	> 400 vehicles/hour
Peak hourly cyclist load (Q_{bh})	≤ 20 cyclists/hour	20 – 50 cyclists/hour	> 50 cyclists/hour
Maximum speed of motor vehicles (Vr)	≤ 30 km/h (physically regulated)	≤ 50 km/h	> 50 km/h
Public transport intensity (Q_{JP})	Not significant	≤ 10 buses/hour	> 10 buses/hour
Minimum width	Not defined	1.25 m	2.00 m
Curve radius	Adapted to the vehicle	10 – 40 m	> 2 m in intersection zones
Marking	Traffic signs	Horizontal signalization, color or different background	Physical barriers (curbs, dividing strips)
Traffic protection	No protection	Not physically separated	Completely separated from the roadway
Maximum longitudinal slope	Up to 6%	Up to 5 % (recommended)	Up to 6 % (shorter sections), up to 3 % on longer sections
Recommended width in high frequency conditions	Not defined	1.50 m	2.50 – 3.00 m

the minimum radius of the vertical convex curve is $R_{kn, min}$ = 30 m, the minimum radius of the vertical concave curve is $R_{kv, min}$ = 10 m. The maximum slope lengths for the average cyclist are shown in Table 2: It is necessary to note that the vertical flow of the cycling surface is conditioned by the vertical flow of the roadway along which it extends.

Slope [%]	**Maximum slope length** [m]
10	20
6	65
5	120
4	250
3	250

Table 2. Maximum slope length [11]

2.2. Traffic load

Traffic load plays a very important role in road design, pavement structure design and traffic management. The total equivalent traffic load is the calculated value of the total number of standard axles during the design period on the relevant traffic lane used for dimensioning [13].

A standard axle is a single axle of a vehicle loaded with a force of 82 kN. It should be emphasized that when calculating the total equivalent traffic load, the analysis does not include passenger vehicles, due to their insignificant impact on pavement structures. By applying the equivalency factor, the number of standard axles, loaded with a force of 82 kN, passing through the relevant dimensioning lane is calculated. Also, when calculating the equivalent traffic load, the following factors are taken into account:

- average annual traffic increase rate,
- traffic load distribution across lanes,
- average load capacity and utilization of heavy duty vehicles,
- axle load of representative vehicle types,
- average annual daily number of heavy duty vehicles in the initial year of operation.

Table 3. Traffic load distribution according to the SRPS U.C4.010 standard [13]

Traffic load group	**Total equivalent axle load of 82 kN in the design period**
Very heavy	$> 7 \cdot 10^6$
Heavy	$2 \cdot 10^6 - 7 \cdot 10^6$
Average	$7 \cdot 10^5 - 2 \cdot 10^6$
Light	$2 \cdot 10^5 - 7 \cdot 10^5$
Very light	$< 2 \cdot 10^5$

The traffic load classification applied by the algorithm is based on the classification given in the SRPS U.C4.010 standard. According to this standard, traffic load can be divided into five groups. Table 3 shows the distribution of traffic load by groups and number of standard axles.

3. Functional classification of urban roads

The city's road network is divided into two functional groups [14]:

- **primary urban network** which has the function of connecting urban areas and is intended for different types of vehicles (public transport, passenger cars, trucks, pedestrians, cyclists),
- **secondary local network** whose function is to access locations and facilities immediately adjacent to the street section. It primarily serves cars, pedestrians and cyclists.

The city's road network consists of a network of streets that can be divided into three groups according to their function:

- access streets,
- collecting streets,
- main streets (boulevards).

Access streets are the most numerous category of urban roads. They can be divided into basic and mixed types. The mixed type has the function of collecting vehicles from a smaller urban area or part of it, while the basic type serves only locations, or peripheral facilities. Street parking areas for motor vehicles can be organized within the access street profile.

Collecting streets create a connection between the primary and secondary road networks. If a collecting street has the primary function of serving a location, in relation to connecting traffic, then it falls into the local road network and belongs to the mixed type.

Main streets belong to the primary road network, have the function of connecting individual urban areas with certain centers of activity and can be connected to regional roads. These are high-capacity roads intended for public and individual passenger traffic. They contain one lane for each direction of vehicle movement, separated by a median strip or median lane.

4. Algorithm description

The algorithm for finding and placing bicycle infrastructure within the existing road profile is divided into five key phases. Each phase will be described below. Figure 1 shows the division of the algorithm into the mentioned phases.

Each phase is divided into a series of clearly defined steps. The algorithm is very comprehensive and was developed in accordance with the key requirements and problems that were revealed by the analysis of bicycle traffic at the level of urban area or city. Given the scope, number and complexity of the problems and requirements, and for the sake of more optimal and comprehensive solutions, as mentioned earlier, the algorithm is divided into five phases. This division was necessary in order to perceive and understand most of the challenges of bicycle paths and urban areas, but also the compatibility of a number of proposed solutions and measures for overcoming possible problems, as well as their prediction and protection from them.

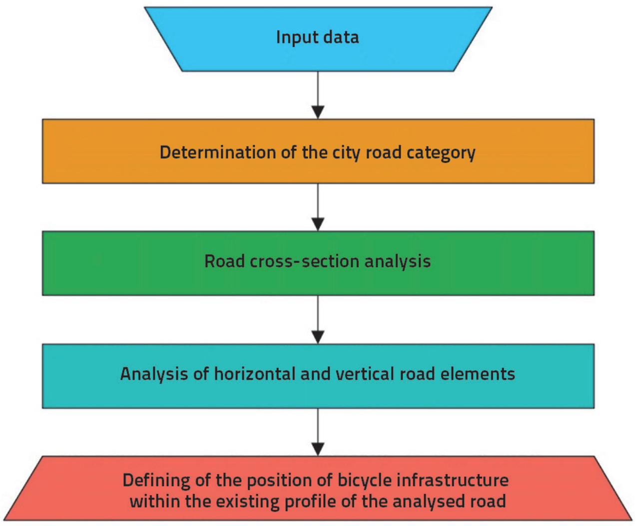

Figure 1. Algorithm presentation by phases

4.1. Phase I – Data entry

In order to solve a complex problem such as bicycle infrastructure, it is necessary to clearly define current and potential causes, as well as their connections and potential mutual causality. The input parameters of the algorithm in question can be divided into two groups:

- geometric parameters (number and width of traffic and road lanes, width of pedestrian paths, existence and width of a green dividing strip between road lanes, existence of tree lines, etc.),
- traffic parameters (city road category, whether the road is one-way or two-way, traffic flow, etc.).

The first phase of the algorithm is the selection and identification of all relevant elements of the traffic and free profile of the road that directly and indirectly affect the bicycle paths, and thus its position as well as geometry of the bicycle infrastructure.

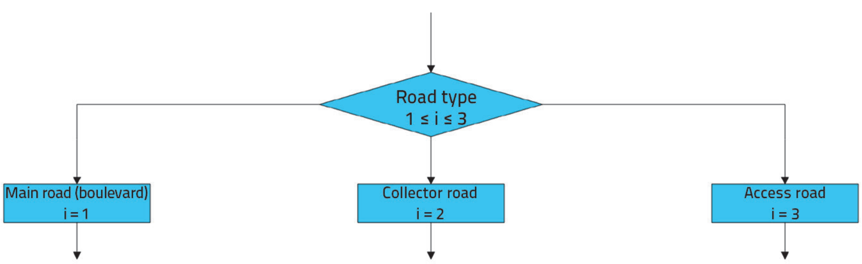

Figure 2. Diagram showing the second phase of the algorithm

4.2. Phase II – Determination of the category of the city road

The second phase is a detailed analysis of the data and parameters entered in the previous phase of the algorithm. In this part of the algorithm, the key part is the classification of the analyzed road according to the category criterion. Given that this is a city transport infrastructure, types of roads can be access roads, collecting or main roads. After the first phase and data entry, the second phase of analysis began. For more efficient functioning and classification of streets, the variable i was applied, and, depending on the category, the variable i can have the value 1 for main roads, 2 for collecting roads or 3 for access roads. The values are variable and determine the further course of the algorithm. From this phase, the algorithm begins to branch into three major branches. Given that the categories of city roads are different, their cross-section geometry, traffic density and traffic intensity are also different. Accordingly, it was necessary to carry out the aforementioned branching. Each of the above categories of city roads has its own specificity, as well as different priorities that needed to be analyzed. Figure 2 shows a part of the algorithm in which branching occurs according to the road category criterion, as described in the text.

4.3. Phase III – Analysis of geometric elements of the road profile

The third phase of the algorithm analyzes the geometric elements of the traffic and free profile of the analyzed city road. Geometric profile elements primarily include the widths of roadways and traffic lanes, as well as the widths of pedestrian walkways. Each level of city traffic has its own specificities and priorities.

For example, on main roads, it is very important to connect centers to which a large number of people gravitate, such as shopping centers, recreational areas, cultural facilities, etc. This criterion is not of great importance for access and collecting streets. Many criteria have indirect links to the safety of road users, especially cyclists. If there is a public transport lane in the traffic profile, it is not possible to implement a bicycle lane on the roadway, so it is necessary to find an optimal solution for the location of the bicycle path. This criterion exists to increase cyclist safety. The public transport lane and bicycle paths are generally located along the right curb of the roadway, so conflict points may arise during traffic flow.

The third phase of the algorithm can be considered a crucial phase. Upon completion of this phase, a preliminary solution is obtained for the position of the bicycle infrastructure, such as a bicycle path, lane or mixed profile. It is necessary to note that if a city road has variable width of cross-section elements (primarily pedestrian roads), an analysis should be performed by section. In this case, the sections to be analyzed must be selected so that, along the entire length, the width of the geometric elements does not deviate by more than ±15 cm.

These potential problems arise as a result of deviation of the regulation line. The aforementioned causes systemic problems, as mentioned before. The solution to this problem lies in the domain of urban planning and urban procedures and is not the subject of algorithm analysis.

This paper will analyze one road from each category, along with a report with a final proposal for measures for the placement of bicycle infrastructure. The algorithm can be divided into three parts or three branches based on the city road category, as described in phase II. For main roads, the analyzed data is as follows:

- width of the pedestrian walkway,
- the existence of a tree line,
- the existence of pedestrian facilities,
- the existence of public transport lanes,
- the presence of public facilities (shopping malls, cultural facilities, parks, etc.).

In the case of a main road, the variable i has the value 1. This is followed by a query to check whether the width of the pedestrian path is greater than 3 m. If not, the algorithm provides a preliminary solution that suggests placing a one-way bike lane in each lane. If the specified condition is met, the next query checks whether the tree line exists. If there is no tree line, a solution is proposed that envisages the placement of a two-way, degraded bicycle path. If the algorithm determines the existence of a tree line based on the entered data, it further checks for the presence of pedestrian facilities on a section of the pedestrian paths. If there are no facilities, the algorithm suggests the creation of a two-way bicycle path painted in red on a section of the pedestrian path with lower pedestrian traffic intensity. Otherwise, it is proposed to place a one-way bicycle lane in each roadway, along the right curb of the roadway. This is followed by an examination of the intensity of the traffic load. The traffic load analyzed for main roads can be very light, light, medium, heavy, and very heavy [13]. To make the algorithm work more efficiently, the following designations are assigned to the loads:

i – very light traffic load,
j – light traffic load,
k – average traffic load,
l – heavy traffic load,
m – very heavy traffic load.

If the traffic load of the main road is light or very light (i or j), the algorithm suggests creating a one-way bicycle lane on the roadway with associated horizontal and vertical traffic signals. Otherwise, if the traffic load is average, heavy or very heavy (k, l or m), the algorithm predicts the placement of a two-way bicycle path, separated by a curb and painted red, along the left edge of the pedestrian path.

Then we touch upon the next condition which uses the variable j. This variable can have a value of 1 or 2, depending on whether the proposed solution is a bike path or a path, respectively. If the variable j has the value 1, i.e., if a bicycle lane is planned,

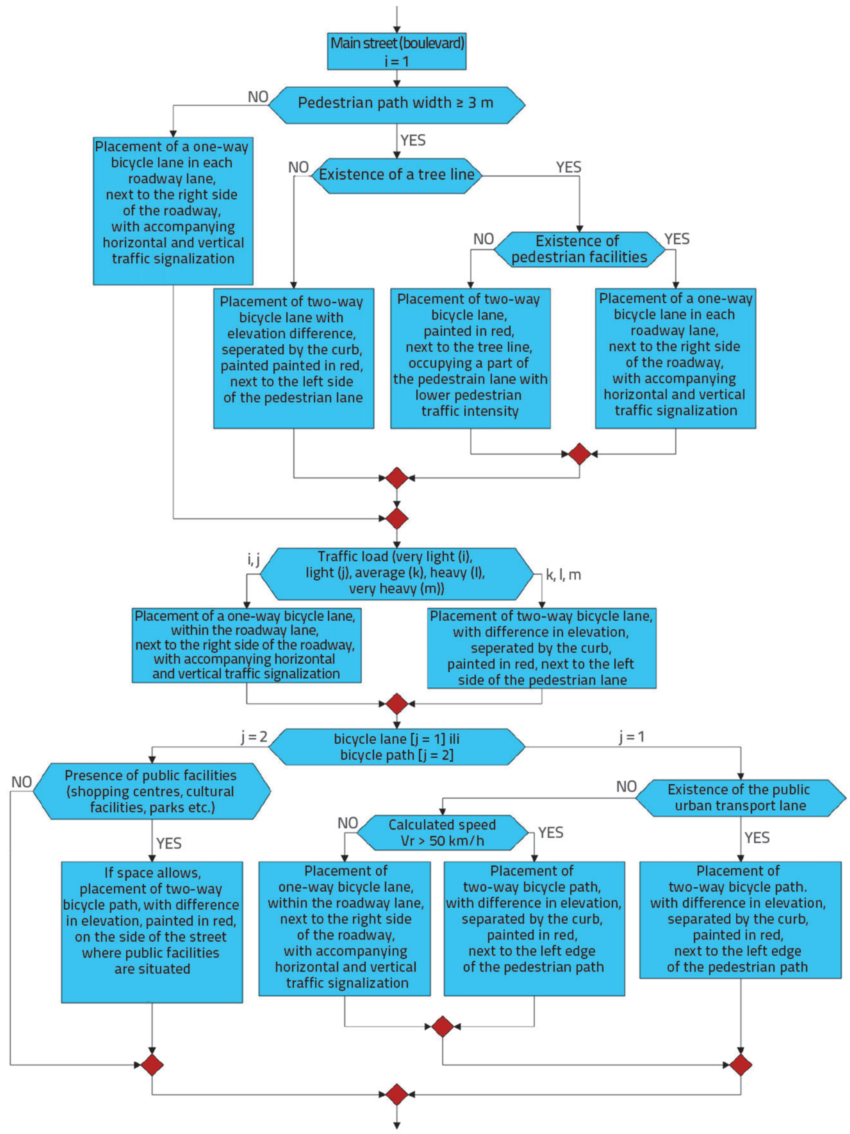

Figure 3. Analysis of geometric elements of the main road profile

the algorithm enters the next query that checks whether there is a lane intended for public transport. If the condition is met, the conceptual design of this phase envisages the creation of a bicycle path, with difference in elevation, separated by a curb, which is placed along the left edge of the pedestrian path. Otherwise, the algorithm checks whether the calculated speed is greater than 50 km/h. If so, it is proposed to build a two-way bicycle path, with difference in elevation, separated by a curb and painted red, along the left edge of the pedestrian path. If the design speed is less than or equal to 50 km/h, it is proposed to create a one-way bicycle lane on a part of the roadway, along the right edge of the roadway, with the corresponding horizontal and vertical traffic signals. Then, if variable j has the value of 2, the algorithm checks for the existence of public facilities that are connected to the main road. If this is the case and if there is enough space, a conceptual solution is proposed that establishes a two-way bicycle path, with a difference in elevation, on a section of the pedestrian path, on the side of the road where public facilities are located.

Figures 3, 4 and 5 show part of the algorithm for the main, collecting and access roads, respectively.

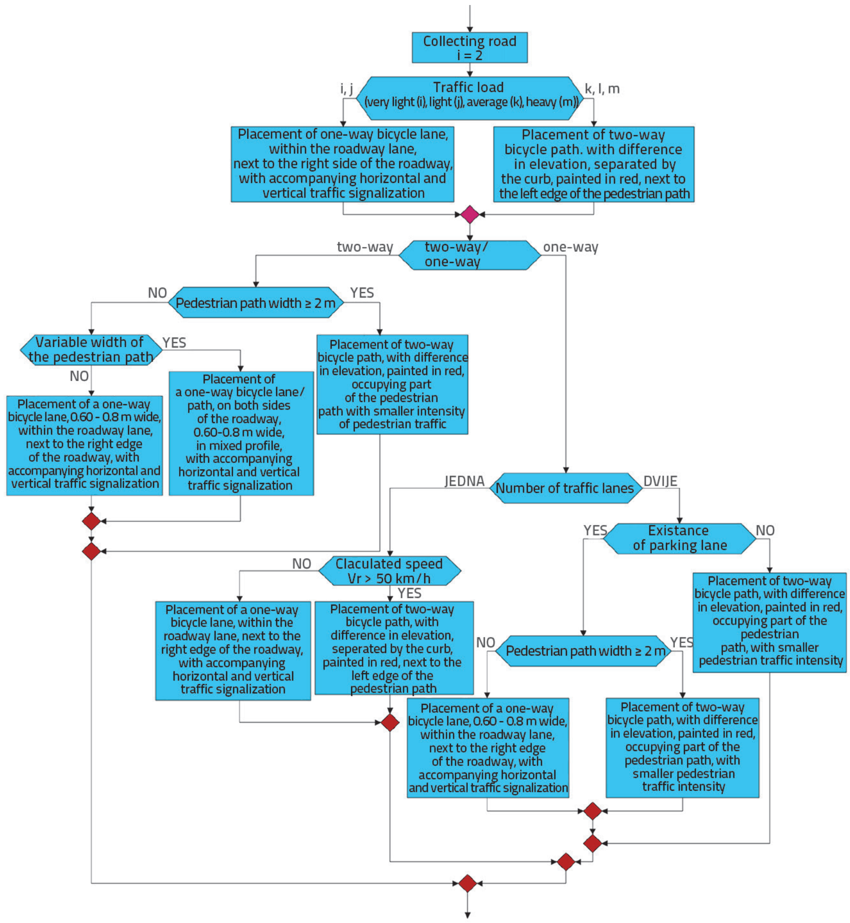

Figure 4. Analysis of geometric elements of collecting road profiles

In the part of the algorithm that analyzes collecting streets, there are certain differences in accordance with the differences between the collecting street and main street profiles. If the street belongs to the collecting category, it follows that i = 2. The first step in analyzing collecting streets is analyzing traffic load. Depending on the intensity, the following designations are assigned to the traffic load:

- i – very light traffic load,
- j – light traffic load,
- k – average traffic load,
- l – heavy traffic load,

If the traffic load is light or very light (i or j), the query proposes creating a one-way bicycle lane on a section of the roadway, along the right edge of the roadway, with associated horizontal and vertical signalization. Otherwise, if the traffic load is average or heavy (k or l), it is proposed to create a two-way bicycle path with difference in elevation, painted red, along the left edge of the pedestrian path. This is followed by a query that checks whether the collecting street is one-way or two-way. If it is one-way, the algorithm checks whether there is one or two traffic lanes. If there is one, a query follows that checks whether the calculated speed is greater than 50 km/h. If the condition is met, the algorithm predicts the creation of a two-way bicycle path with difference in elevation, otherwise it proposes the creation of a one-way bicycle lane on a section of the roadway, along the right curb of the roadway. If there are two traffic lanes, the following condition checks whether there is a parking lane. If the condition is met and the lane exists, the previously described control of the width of pedestrian paths follows. If a parking lane does not exist, the algorithm suggests creating a two-way bicycle path with difference in elevation on a section of the pedestrian path with lower pedestrian traffic intensity.

If the collecting street is two-way, there is a condition that checks whether the width of the pedestrian path is greater than 2 m. If the condition is met, the algorithm suggests the creation of a two-way bicycle path with difference in elevation as a solution, on a section of the pedestrian path with lower pedestrian traffic intensity. Otherwise, a query follows to check whether the width of the pedestrian path is variable and, if so, the creation of a one-way bicycle path/path on both sides of the road, in a mixed profile, is planned. If the width of pedestrian paths is not variable, it is proposed to create a one-way bicycle lane on a section of the roadway, along the right curb of the roadway.

In the part dealing with the analysis of access streets, the first query examines whether the traffic load is light, very light, or average. Traffic loads are indicated by the following symbols:

i – very light traffic load,
j – light traffic load,
k – average traffic load.

If the traffic load is very light or light (i or j), it is proposed to create a one-way bicycle lane on a part of the roadway, along the right edge of the roadway, with associated horizontal and vertical traffic signalization. In case the traffic load is average (k), it is proposed to create a two-way bicycle path with difference in elevation, painted in red, along the left edge of the pedestrian path.

The next criterion is determining whether the street is one-way or two-way. If it is one-way, the algorithm checks whether it has one or two traffic lanes. If there is only one traffic lane, a query follows that checks whether the width of the pedestrian path is greater than or equal to 2 meters. If so, the algorithm predicts the creation of a two-way bicycle path with difference in elevation on the part of the pedestrian path with lower pedestrian traffic intensity, otherwise it predicts the creation of a one-way bicycle path with difference in elevation on the part of the pedestrian paths, on both sides of the roadway. This control of the width of pedestrian paths with its outcomes is repeated several times in the part of the algorithm that analyzes access roads. In the case of a one-way access road with two traffic lanes, the algorithm first checks whether there is a parking lane. If there is, a query follows that checks whether the width of the pedestrian paths is greater than or equal to a width of 2 m, as described previously. If a parking lane does not exist, the algorithm predicts the placement of a one-way bicycle lane on a section of the roadway, along the right edge of the roadway.

If the street is two-way, the algorithm checks whether the width of the pedestrian paths is greater than or equal to 2 m. If so, the algorithm predicts the creation of a two-way bicycle path with difference in elevation, painted in red, occupying a part of the pedestrian path with lower pedestrian traffic intensity. Otherwise, it is proposed to create a one-way bicycle lane on a part of the roadway, along the right edge of the roadway, with associated horizontal and vertical traffic signalization.

4.4. Phase IV – Analysis of horizontal and vertical road elements

The fourth, and final, phase of the algorithm starts from the preliminary solution for the placement of bicycle infrastructure from the previous phase. Accordingly, an analysis of geometric elements is performed. The fourth phase can be divided into three parts (sub-phases) according to the type of analysis performed:

- horizontal geometry analysis,
- vertical geometry analysis,
- analysis of transverse slopes.

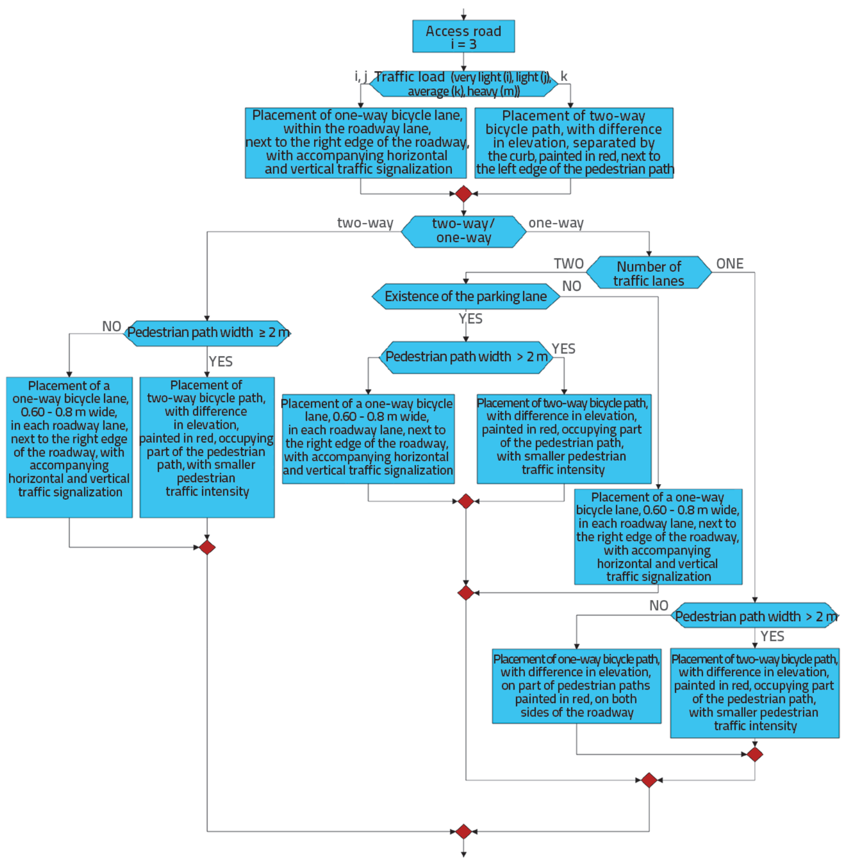

Figure 5. Analysis of geometric elements of the access road profile

Given that there is a preliminary solution for the placement of bicycle infrastructure, the number of geometric elements is entered at this stage. During the analysis, the input parameters are the number of horizontal and vertical curves, calculation speed, and the number of elevation breaks. Figure 6 shows the input parameters, as well as the part of the algorithm that represents the fourth phase.

Each of the listed entered parameters is designated by its own designation, as shown in Figure 6. To analyze the geometry of each curve individually, loops *while* and *repeat until were introduced*. Given the complexity of the problem, and in order to optimize time, certain counters were introduced. Counters have the function of preventing the occurrence of an infinite loop, i.e., a possible situation in which the condition for entering the loop is always met.

In this phase, the input and analysis of geometric elements is solved by using a sequence, or by forming a sequence of elements of the same type (e.g., a sequence of elements of the radius of horizontal curves). All horizontal and

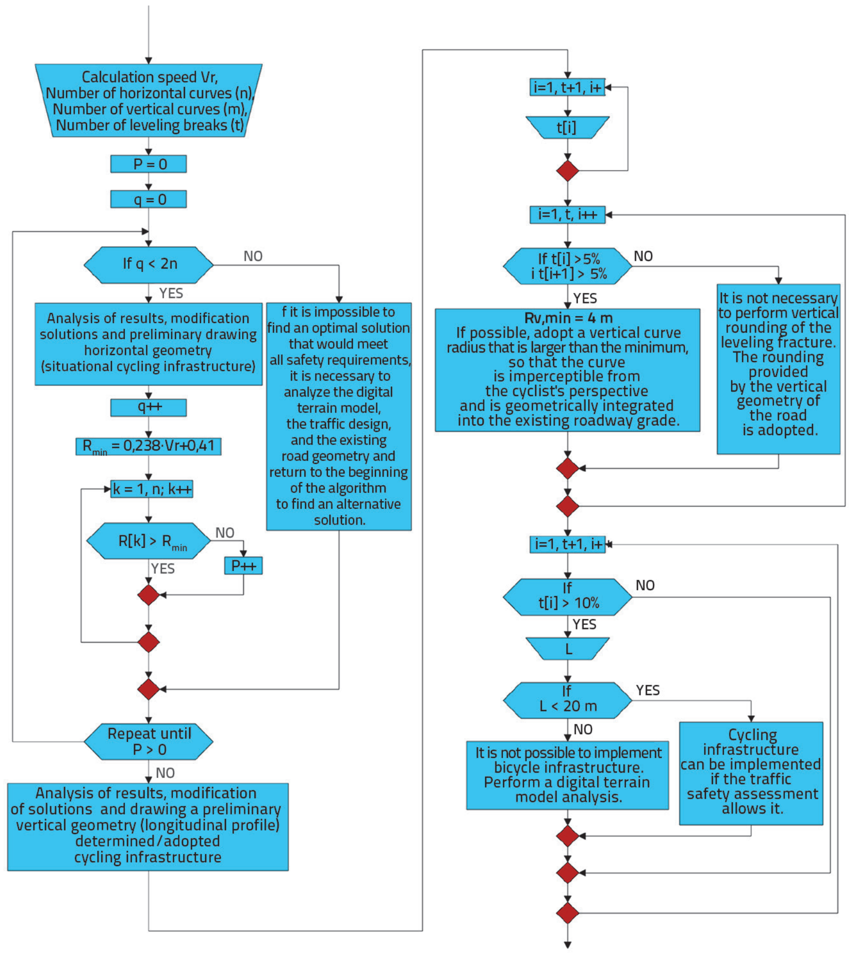

Figure 6. Phase IV - analysis of horizontal and vertical geometry

vertical geometry criteria used in the development of the algorithm were taken from the manual on road design in the Republic of Serbia [11]. That way, the algorithm was synchronized with current regulations and standards. The input data for this phase are:

- computational speed (Vr),
- number of horizontal curves (n),
- number of vertical curves (m),
- number of elevation breaks (t).

Furthermore, the following parameters have been introduced:

P – number of horizontal curves with a radius smaller than the minimum,

q – number of loop iterations.

The initial values of the parameters P and q have the value 0. The first part of this phase is the analysis of the horizontal geometry of the road. This phase consists of one *repeat-until* loop whose condition is that the analysis is carried out as long as the parameter P has a value greater than 0. At the beginning of the loop, the first step is to check whether the number of iterations (q) is less than twice the number of horizontal curves (2n) (Figure 6). If this condition is not met, then it is not possible to find an optimal road solution, so the algorithm suggests additional analysis of the digital terrain model, traffic design, road geometry, etc. Otherwise, the preliminary solution, given in the previous phase, is analyzed, modified, and plotted, after which the value of the parameter q is increased by 1. Then, the algorithm calculates the minimum radius of the bicycle infrastructure, according to the formula:

$$R_{min} = 0{,}238 \cdot Vr + 0{,}41$$

It is followed by the loop *for* which ranges from 1 to n and compares the value of each radius of the horizontal curve individually with the previously calculated minimum value. If there is a radius whose value is not greater than the minimum one, the parameter P increases its value by 1. This parameter is contained in the main loop condition and enables its operation. Given that an infinite loop may occur, a parameter q was introduced that would interrupt the loop when the number of iterations exceeds twice the number of horizontal curves. After this part, the results are analyzed again and a preliminary solution of the vertical geometry is plotted. Then, using a loop *for*, a sequence of elements whose longitudinal slopes are the road level is entered and formed. The mentioned loop *for* ranges from the value 1 to t + 1, where the parameter t is the number of elevation breaks. By creating this sequence, it is much easier to see the longitudinal geometric elements of the road. Then, by using the loop *for*, the values of the formed sequence are examined. In fact, the algorithm tests whether two consecutive elevation slopes have an individual value greater than 5 %. If the condition is met, the algorithm suggests taking a radius that is larger than the minimum, if possible, ($R_{v,min}$ = 4 m) [15]. Otherwise, the vertical alignment of the proposed bicycle infrastructure solution should not be vertically rounded. The last part of this phase is the analysis of longitudinal slopes from the perspective of urban cycling conditions [11]. By applying a new loop *for*, the algorithm goes through the previously formed sequence and checks whether the individual value of each longitudinal slope is greater than 10 %. If this is not the case, the algorithm terminates and the proposed solution becomes final. Otherwise, the length L is entered, which is the length of the section on which the elevation is at a slope greater than 10 %. It is then checked whether the value of the entered length L is less than 20 m. If it is, the algorithm finishes its work and the proposed solution becomes final. Otherwise, the algorithm determines that it is not possible to implement the proposed bicycle infrastructure solution under the given conditions and suggests additional analysis of the digital terrain model.

4.5. Phase V – Defining the position of bicycle infrastructure within the existing profile of the analyzed road

The fifth and final phase is the end of the algorithm itself. In this phase, all geometric elements are accepted based on previously defined criteria, i.e., phases. The data obtained is ready for further elaboration and the start of the development of a conceptual solution for bicycle infrastructure. The data is presented in the form of a report that will be presented in the following chapters.

5. Application of the developed algorithm

The algorithm will be tested by analyzing the existing infrastructure. The analysis will cover three roads: access, collecting and main roads. Input data relating to the geometry of the road were obtained by reviewing the construction permit projects. The mentioned projects were obtained from the Public Enterprise Institute of Urban Planning of the City of Niš for the purpose of scientific research.

5.1m Access street analysis

The analyzed street, which falls into the access category, is Franca Vintera Street. The location of the analyzed street is shown in Figure 7. The total length of the street, which is shown in Figure 8, is 246.88 m and contains 19 transverse profiles.

The street has two roadway lanes, with one traffic lane each, as well as pedestrian walkways on both sides of the roadway. The width of the roadway and traffic lanes is 3.00 m, so the total width of the roadway is 6.00 meters. The pavement is bordered on both sides by a recessed curb measuring 18/24 cm. The total difference in elevation between the roadway and pedestrian walkway is 6 cm. The pavement structure is flexible, made of asphalt AB11s (5 cm), BNS32 (7 cm) and unbound materials in the form of crushed stone aggregate 0-31.5 (20 cm) and gravel 0-63 (25 cm). The pavement structure of pedestrian roads is identical to the pavement. The width of the left pedestrian path is 5 m, while the width of the right one is 4.72 m. Although the widths of pedestrian paths are variable, the difference is very small compared to the width of the road, so the aforementioned differences can be ignored. The transverse slope of the roadway is single-lane (from the left to the right edge of the roadway) and is 3 % along the entire length of the street. The transverse slope of the left pedestrian path is 3 % up to profile 8 (km 0+101.63), and 2 % up to the last profile, while the transverse slope of the right pedestrian road is constant and is 2 %. The transverse slopes of pedestrian paths are oriented towards the axis of the roadway to drain stormwater and prevent it from accumulating on pedestrian paths.

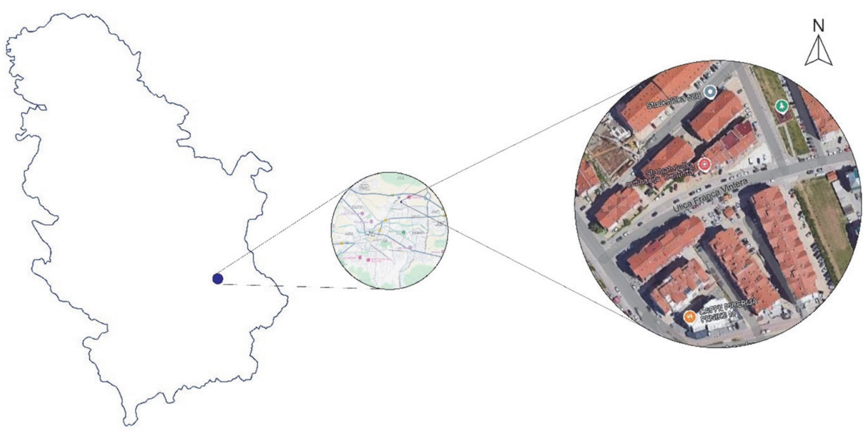

Figure 7. Location of Franca Vinetra Street in Niš

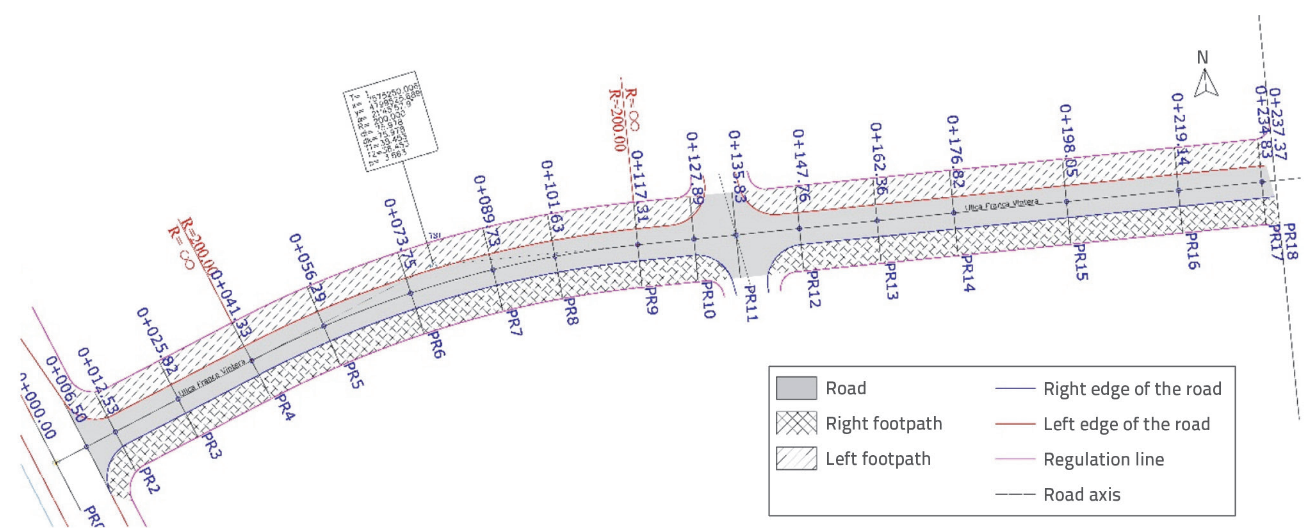

Figure 8. Situation plan of Franca Vintera Street

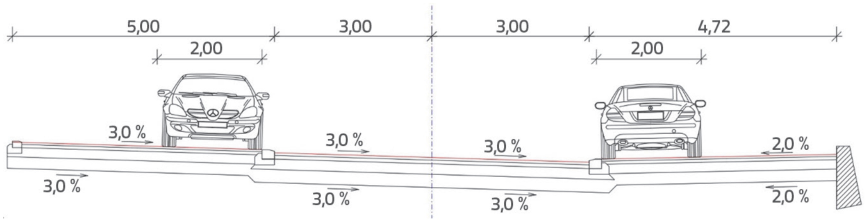

Figure 9. Characteristic cross-section profile of the access road

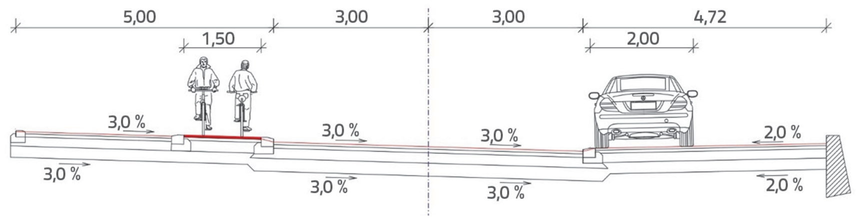

Figure 10 Proposed solution within the cross-section of Franca Vintera Street

The longitudinal slope of the roadway is 2.3 % from the beginning of the street to the km 0+073.74 m mark and 1.4 % to the last profile. The longitudinal slopes are positive, i.e., the analyzed street is elevated in terms of station increase. At the elevation break, there is a vertical convex curve with a radius of R = 15,000 m. On the situational plan, one horizontal curve with a radius of R = 200 m, with a deflection angle of α = 21° 45′ 58′′, can be observed between profile 4 (km 0+041.33) and profile 9 (km 0+117.31). The aforementioned curve is oriented to the right in the direction of station increase. Figure 9 shows a characteristic cross-section of Franca Vintera Street, with parallel parking of motor vehicles indicated.

Given that this is an access road, as defined by the algorithm, i = 3. The first query of this branch of the algorithm is an analysis of traffic load intensity. The traffic load of the analyzed access street falls into the average load category. Based on this information, it is proposed to place an bicycle path with difference in elevation along the left edge of the pedestrian path, separated by a curb and painted red. This is followed by a query that analyzes traffic management, i.e., whether the street is designed for one-way or two-way traffic. In this particular case, it is a two-way street. After that, an analysis of the width of the pedestrian paths is carried out. The width of the pedestrian paths is greater than 2 m and it is proposed to place a two-way bicycle path, which has a difference in elevation and is separated from the pedestrian path by a curb. The algorithm dictates that the bicycle path be located on a section of the pedestrian path that has a lower level of pedestrian traffic. Given that in this specific case there are residential buildings on both sides of the analyzed street, it can be considered that the difference in pedestrian traffic intensity is negligible, leaving the designer with room to choose the side of the street on which the bicycle lane will be constructed. Accordingly, the optimal position of the bicycle path would be on part of the surface of the left pedestrian path, since it has a greater width. The accepted width of the bicycle path is t_b = 1.5 m.

Upon completion of this branch of the algorithm, geometry analysis is initiated. The input data for the next phase are the number of vertical and horizontal curves, as well as the number of elevation breaks (this data is equal to the number of vertical curves). As stated earlier, the street has only one horizontal curve (n = 1), one vertical curve (m = 1), and one elevation break (t = 1). The design speed of this road category is 40 km/h, so in the first step of this phase, the minimum radius of horizontal curves can be determined, according to the formula [15]:

$$R_{min} = 0.238 \cdot V_r + 0.41 \qquad (1)$$

so the value of the minimum radius of horizontal curves is R_{min} = 9.93 m.

Given that the bicycle path is positioned on the left side of the roadway, closer to the apex of the horizontal curve, the radius of the bicycle path is $R_b = R+t_s+t_b/2$, where

R – radius of the horizontal curve of the analyzed road (200 m),
t_s – width of the roadway (3.0 m),
t_b – width of the bicycle path (1.5 m).

Therefore, the radius of the bicycle path is 203.75 m. The radius of the bicycle path is greater than the minimum radius value, which makes the condition R > R_{min} fulfilled.

Then, an analysis of vertical curvatures is performed. The algorithm enters a loop in which it analyzes a sequence of elements whose values are consecutive slopes. The street elevation has only one break, i.e., two slopes, so the number of elements in the sequence is 2. The aforementioned loop aims to test whether two consecutive slopes are individually greater than 5 %. If they are, the curvature of the road's elevation is taken into account. As previously stated, the values of successive elevation slopes are i_1 = 2.3 % and i_2 = 1.4 % (in terms of station increase). Both slopes of the elevation are less than 5 %, so the algorithm defines that the minimum radius of the vertical curve must be $R_{v,min}$ = 4 m. Given that the project defines a vertical curve, the radius of which is 15,000 m and is greater than the minimum value $R_{v,min}$, the designed radius is also taken on a part of the bicycle infrastructure. Then, the algorithm analyzes longitudinal slopes of the elevation, which are greater than 10 %, and the length of the sections affected by that slope. Given that the road elevation has slopes of values less than 10 %, this step completes the algorithm and generates the report shown in Table 4.

During the inspection of the road, it was noticed that parking spaces for parallel parking were marked on both the left and right pedestrian paths. Therefore, parking spaces should be removed from the left pedestrian path, in order to provide space for the bicycle path predicted by the algorithm. Figure 10 shows a proposed solution for the location of the bicycle path within the cross-section of Franca Vintera Street.

Table 4. Analysis report and proposed solution for the placement of bicycle infrastructure on the access road

Input data for Access road	
Street name	Franca Vintera
Length of the analyzed section	246.88 m
Traffic load	Average
Number of traffic lanes	2
Number of traffic lanes per direction	1
Traffic lane width	3.0 m
Width of the left pedestrian lane	5.0 m
Width of the right pedestrian lane	4.72 m
Number of vertical curves	1
Radii of vertical curves	R_{v1} = 15000 m
Number of horizontal curves	1
Radii of horizontal curves	R_1 = 200 m
Number of elevation breaks	1
Longitudinal slopes of the elevation	i_1 = 2.3 %. i_2 = 1.4 %
Type of transverse slope of the roadway	One-way
Transverse slope of the pavement	3 %
Transverse slope of the left pedestrian path	2-3 %
Transvesre slope of the right pedestrian path	3 %
PROPOSED SOLUTION	
Type of bicycle infrastructure	Bicycle path
Position	On the left pedestrian path
Direction of bicycle traffic	Two-way
Width	1.5 m
Curbside elevation	Yes
Transverse slope	3 %
Number of horizontal curves	1
Radii of horizontal curves	R_1 = 203.75 m
Number of vertical curves	1
Radii of vertical curves	R_{v1} = 15000 m
Additional measures	Paint the pavement surface red
Traffic signs	Mark the area with horizontal and vertical traffic signs

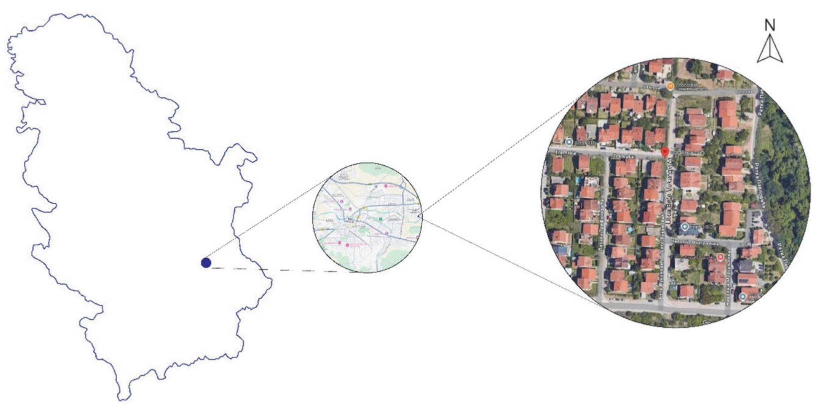

Figure 11. Location of Bete Vukanovića Street in Niš

5.2. Collecting street analysis

The collecting street subjected to further analysis is Bete Vukanovića Street, shown in Figure 11. The project review included an analysis of the geometric elements of the situational plan, i.e., longitudinal and transverse profiles of the aforementioned road. The street contains 26 cross-sections, as shown in Figure 12. The last cross-section is at a distance of 208.45 m, which is the total length of the street.

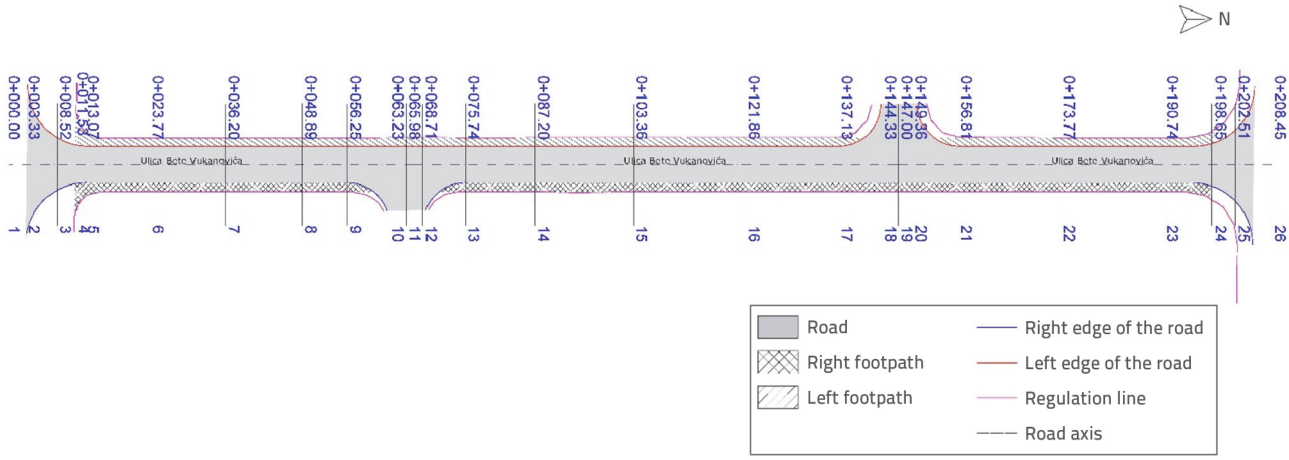

Figure 12. Situational plan of Bete Vukanovića Street

No horizontal curves were observed on the situational plan (Figure 12).

The street contains two traffic lanes with one lane in each direction. The width of the traffic lane is 3 m, so the total width of the roadway is 6 m. The roadway is separated from pedestrian paths by a recessed curb, with a 6 cm difference in elevation. The transverse slope of the roadway is single-lane, and is 2 % and oriented from the left to the right curb. The width of pedestrian paths varies from profile to profile. However, the difference in width is negligible and a value of 1.5 m can be taken as the average value of the width of pedestrian paths on all cross-sections. Both pedestrian paths have a single slope towards the roadway, which is 2 %. The pavement structure is flexible and consists of asphalt layers and layers of mineral mixtures. The asphalt layers consist of an AB11 asphalt wearing course (5cm) and a BNS32 bituminous base course (7cm). The layers of the pavement structure made of unbound layers consist of crushed stone aggregate 0-31.5 (20cm) and a layer of gravel-sand material of fraction 0-63 (25cm). Figure 13 shows a characteristic cross-section of Bete Vukanovića Street.

The elevation in the longitudinal sense has 6 breaks and 6 vertical curves, of which 4 are concave and 2 are convex. The maximum radius of vertical curves is 2000 m, while the minimum is 100 m. The maximum longitudinal slope of the elevation is 8.11 %, while the minimum is 0.22 %.

This brief analysis served to prepare the input data for the algorithm. Since the analysis of a collecting street is being performed, it follows that i = 2 and the second branch of the algorithm is initiated. The first query in this branch relates to the predicted traffic load. The traffic load of the analyzed collecting street falls into the light category, so it is proposed to place a bicycle lane on part of the roadway, along the right edge of the roadway, with associated horizontal and vertical traffic signals. The next query relates to the planned traffic arrangement, i.e., whether the street is planned for one-way or two-way traffic. Given that this is a two-way street, the next query relates to the width of the pedestrian path. This step analyzes whether the width of pedestrian paths is greater than 2 m. As stated before, the width is 1.5 m, so the next query is initiated. The following query determines whether the width of pedestrian paths is constant or variable. The width is not constant, but is negligibly small, which is why an average width of 1.5 m was taken. After this step, the algorithm provides a preliminary proposal for the position of the bicycle infrastructure. The proposed solution is a one-way bicycle lane at road level, for each direction, accompanied by proper horizontal and vertical traffic signals. Also, a lane width ranging from 0.6 to 0.8 m has been proposed. This value is indicative, leaving room for the traffic infrastructure designer to assess and make their own decision about the width of the bicycle lane.

Then, the analysis enters the next phase of the algorithm, which is the analysis of the road geometry. The first step of this phase is the analysis of the horizontal geometry of the road. Given that there are no horizontal curves, but the road is straight, the proposed bicylce infrastructure will also be straight. Then, the value of the longitudinal slope of the elevation is entered. The road contains 7 longitudinal slopes, i.e.:

i_1 = 2,01 %
i_2 = 8,11 %
i_3 = 2,75 %
i_4 = 0,91 %
i_5 = 1,30 %
i_6 = 0,22 %
i_7 = 3,86 %

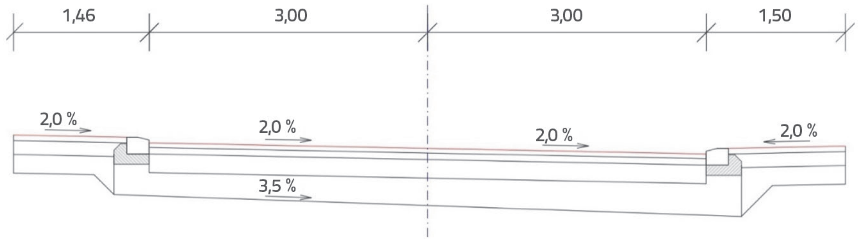

Figure 13. Characteristic cross-section profile of a collecting street

Table 5. Analysis report and proposed solution for the placement of bicycle infrastructure on the collecting road

Input data for Collecting road	
Street name	Bete Vukanovića
Length of the analyzed section	208.45 m
Direction of vehicle movemen	Two-way
Traffic load	Light
Number of traffic lanes	2
Number of traffic lanes per direction	1
Traffic lane width	3.0 m
Width of the left pedestrian lane	1.5 m
Width of the right pedestrian lane	1.5 m
Number of vertical curves	6
Radii of vertical curves	R_{v1} = 100 m. R_{v2} = 150 m. R_{v3} = 400 m. R_{v4} = 600 m. R_{v5} = 2000 m. R_{v6} = 600 m
Number of horizontal curves	0
Radii of horizontal curves	R_1 = 200 m
Number of elevation breaks	6
Longitudinal slopes of the elevation	i_1 = 2.01 %. i_2 = 8.11 %. i_3 = 2.75 %. i_4 = -0.91 %. i_5 = 1.30 %. i_6 = 0.22 %. i_7 = 3.86 %
Type of transverse slope of the roadway	One-way
Transverse slope of the pavement	2 %
Transverse slope of the left pedestrian path	2 %
Transvesre slope of the right pedestrian path	2 %
PROPOSED SOLUTION	
Type of bicycle infrastructure	Bicycle lane
Position	Location along the edge of the roadway lane for each direction
Direction of bicycle traffic	One-way
Width	0.6 - 0.8 m
Curbside elevation	No
Transverse slope	2 %
Number of horizontal curves	0
Radii of horizontal curves	/
Number of vertical curves	6
Radii of vertical curves	The bicycle lane takes over the vertical geometry of the roadway
Additional measures	Paint the cycling surface red
Traffic signs	Mark the area with horizontal and vertical traffic signs

By entering this data, a series of elements is formed, the members of which are the values of the longitudinal slopes of the elevation. After that, an analysis of consecutive values is performed, more precisely, do two consecutive slopes have a value greater than 5 %? The answer is affirmative only in two cases, when the analysis of slope i_1 and i_2 and of slope i_2 and i_3 is performed. In the above cases, the algorithm suggests taking a radius larger than the minimum, so that the curve of the elevation is imperceptible from the cyclist's point of view, and determines the value $R_{v,min}$ = 4 m as the minimum value of the radius of the vertical curve. When analyzing these three slopes and the curve of the elevation, it was noticed that the diameters of the vertical curves R_{v1} = 100 m (concave curve) and R_{v2} = 150 m (convex curve) were defined by the road project as greater than the minimum and that the proposed bicycle lane takes over the geometry of the designed road. Then, the algorithm enters the last step of this phase, which refers to the analysis of longitudinal slopes that are greater than 10 %. Since all longitudinal slopes are less than 10 %, this step completes the analysis and generates the report shown in Table 5. Figure 14 shows the proposed solution within the cross-section of Bete Vukanovića Street.

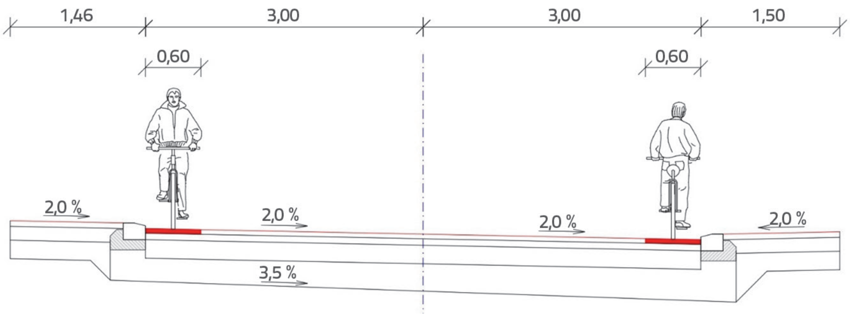

Figure 14. Location of the collecting street bike lane

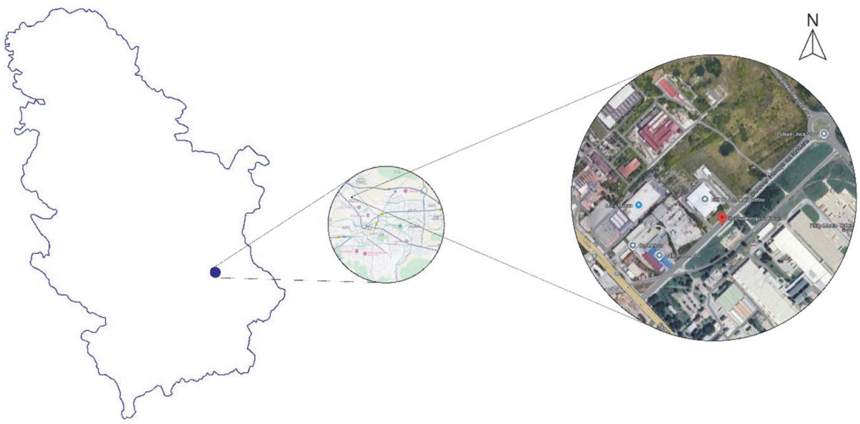

Figure 15. Location of Bulevar Heroja sa Košara in Niš

5.3. Analysis of the main street

The main street analyzed in this paper is Bulevar Heroja sa Košara, shown in Figure 15. The street contains 43 cross sections, with the final station at km 0+746.39, which is the total length of the street, Figure 16.

The street has two roadways with two traffic lanes in each direction. The width of the roadway lanes is 6.5 m and there is a 1.5 m wide median strip between them. Pedestrian paths are located on both sides of the roadway. In terms of station increase, there is a 1 m wide green area on the right side of the roadway along the entire length of the street. The width of the left pedestrian path is 3.0 m, with a single-lane slope of 2.5 % towards the roadway. The width of the right pedestrian path is 5.5 meters with a single-lane slope of 2.5 % towards the roadway. Each roadway lane has a single slope of 2.5 %, oriented from the road axis towards the outer edge of the roadway. Pedestrian paths are separated

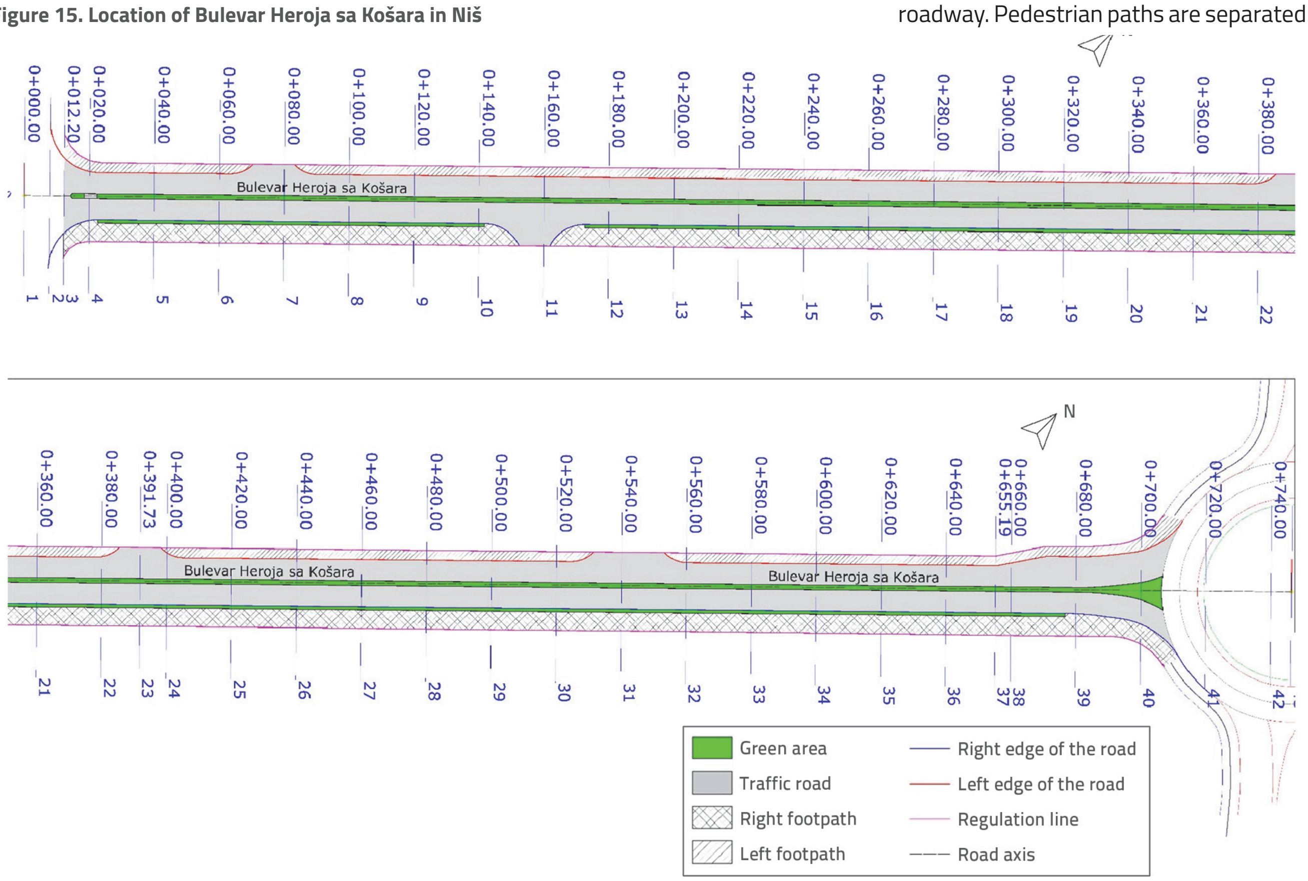

Figure 16. Situational plan of Bulevar Heroja sa Košara

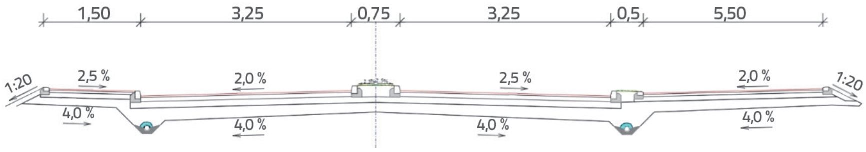

Figure 17. Characteristic cross-section profile of a main street

from the roadway by curbs, with a total elevation difference of 15 cm. The pavement structure of the roadway and pedestrian paths is flexible and consists of asphalt layers AB16s and BNS32s A in thicknesses of 7 and 10 cm, respectively. Below the asphalt layers is a layer of crushed stone aggregate which is 0-31.5 (20 cm) thick and a layer of gravel with a thickness of 0-63 (30 cm). The street does not contain horizontal curves.

The road elevation has only one break, in the longitudinal direction, and one vertical curve. The vertical curve is concave, with a radius of R = 12850 m. Figure 17 shows the characteristic cross-section of Bulevar Heroja sa Košara.

The first input to the algorithm is the category of the city road. In this case it is a main road, thus i = 1. The next step of the algorithm determines whether the widths of pedestrian paths are greater than or equal to 3 m. As previously stated, the widths of both pedestrian paths are greater than 3 m. Then,

Table 6. Analysis report and proposed solution for the placement of bicycle infrastructure on the main road

Input data for Main road	
Street name	Bulevar Heroja sa Košara
Length of the analyzed section	746.39 m
Direction of vehicle movement	Two-way
Traffic load	Average
Number of traffic lanes	2
Number of traffic lanes per direction	2
Traffic lane width	3.25 m
Width of the left pedestrian lane	3.0 m
Width of the right pedestrian lane	5.50 m
Number of vertical curves	1
Diameter of vertical curves	R_{v1} = 12850 m
Number of horizontal curves	0
Diameters of horizontal curves	/
Number of elevation breaks	1
Longitudinal slopes of the elevation	i_1 = 0.3 %. i_2 = 1.6 %
Type of transverse slope of the roadway	One-way
Transverse slope of the pavement	2.5 %
Transverse slope of the left pedestrian path	2.5 %
Transvesre slope of the right pedestrian path	2.5 %
PROPOSED SOLUTION	
Type of bicycle infrastructure	Bicycle path
Direction of bicycle traffic	Two-way
Position	On the right side of the pedestrian path
Width	1.5 m
Curbside elevation	Yes
Transverse slope	0.03
Number of horizontal curves	0
Radii of horizontal curves	/
Number of vertical curves	1
Radii of vertical curves	The bicycle lane takes over the vertical geometry of the pedestrian path
Additional measures	Paint the cycling surface red
Traffic signs	Mark the area with horizontal and vertical traffic signs

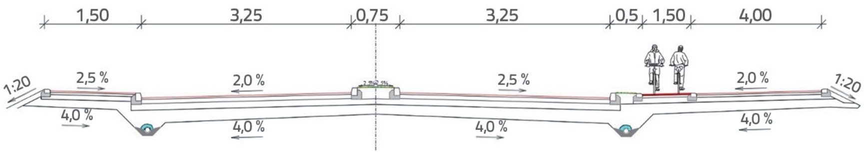

Figure 18 .Location of the main road bicycle path

the algorithm checks for the existence of a tree line. On this road, there is a tree line, i.e., a green area, along the entire length of the street on the right-hand pedestrian road. The following query analyzes the existence of pedestrian facilities (e.g., the existence of benches). Upon checking the constructed condition of the road, no pedestrian facilities were observed. Based on all analyzed conditions, the algorithm provides the first preliminary result, which is a proposal to position a two-way bicycle path, next to a tree line, painted red, with accompanying horizontal and vertical signalization, on a section of the pedestrian path with lower pedestrian traffic intensity. The algorithm then checks the intensity of the traffic load. The traffic load on the analyzed main road is average. Based on this data, the algorithm suggests creating a two-way, bicycle path with elevation difference, separated by a curb. Given that the preliminary solution is a bicycle path, the algorithm continues with the further analysis, thus j = 2. The next step is to check whether there is a lane for public transport vehicles. There are no lanes for public transport on the road. This is followed by a query that checks whether the calculated speed value is greater than 50 km/h. The calculated speed is 60 km/h, so the algorithm suggests creating a two-way bicycle path with elevation difference, painted red and separated by a curb. This step completes phase III of the algorithm and provides a final preliminary solution for the placement of bicycle infrastructure. At the end of this phase, the algorithm suggests placing a two-way bicycle path with elevation difference, painted red, next to the tree line, on a section of the right pedestrian path, with accompanying horizontal and vertical signalization. The proposed width of the bicycle path is 1.5 m.

Then, the algorithm enters phase IV, which is the analysis of road geometry. The first step of this phase is to examine the horizontal curves. Given that the entire road is straight and there are no horizontal curves, this part of the algorithm ends immediately.

In the next step, a sequence of elements is entered that have the value of the longitudinal slopes of the elevation, in terms of the station increase. The elevation has a total of two longitudinal slopes, i.e.: i_1 = 0.3 %, i_2 = 1.6 %.

The algorithm then analyzes the values of the entered sequence. In this analysis, it examines whether the values of two consecutive elevation slopes have a value greater than 5 %. If they have, a minimum radius of vertical curves of bicycle infrastructure is suggested. Given that all longitudinal slopes of the elevation are less than 5 %, the algorithm suggests that the proposed bicycle path maintain the vertical curvature of the main road's elevation. In the next step of this phase, the length of the section where the elevation has a longitudinal slope greater than 10 % is analyzed. All elevation slopes are less than 10 %, so this step ends immediately. Upon completion of this step, a report of the proposed solution for the bicycle infrastructure of the main road is created, and is shown in Table 6. Figure 18 shows a proposed solution for the location of the bicycle path on the cross-section of Bulevar Heroja od Košara.

5.4. Discussion

The analysis conducted in Chapter 5 included the existing infrastructure and the application of the developed algorithm to three types of city roads (access, collecting and main). The algorithm has demonstrated the ability to adapt to the specific conditions of each road, taking into account all the essential characteristics of the road network in urban conditions. The results showed that the algorithm effectively solves the problems of placing bicycle infrastructure within the existing road profile, thereby increasing the functionality of city roads.

6. Conclusion

The conducted analysis showed that the algorithm effectively solves the increasingly pressing problem of locating bicycle infrastructure in urban areas. The algorithm is designed to fit its solution into the existing profile of the city's road, while also leaving enough room for the designer during the final development of the project. By analyzing the access street, the algorithm suggested a 1.5-m-wide bicycle path, on part of the left pedestrian path. Given that the width of the right pedestrian path is sufficient for positioning the bicycle infrastructure, the designer can later perform additional analyses of the position of the bicycle path on the right pedestrian path and make any changes to the final solution.

The bicycle lane was the optimal solution for the collecting street analysis. The width is in the range from 0.6 to 0.8 m. The designer should precisely define this width based on a direct inspection of the road geometry and traffic flow.

The result of the analysis of the main road is the placement of a two-way bicycle path, painted in red, on part of the right pedestrian path. Given that the width of the pedestrian path is large enough and that the street is a high-ranking city road, the designer should accept the width of the proposed bicycle infrastructure solution, so that it fits the geometry and traffic flow with the roads that are connected to the analyzed main road.

The described algorithm is applied exclusively on city roads. Moreover, it does not foresee the placement of bicycle infrastructure in the intersection zone, which represents its limitation. The algorithm described in this paper should help the designer find the optimal solution for the position of bicycle infrastructure in urban areas.

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