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Route optimization for bicycle users

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Abstract

The increasing pressure to use environmentally friendly modes of transportation also demands the development of advanced navigation tools focused on these vehicle types. Cyclists, for example, have different preferences and needs that go beyond current routing algorithms that often prioritize distance and time, neglecting safety, comfort, and efficiency, leading to unsafe, unpleasant, or inefficient routes that could discourage cyclists from using a bicycle as their primary mode of transportation. To address this problem, this dissertation proposes a different approach to routing that incorporates optimization parameters for cyclists and enables personalized route selection, opening the way for cyclists to plan and find routes that are not only focused on distance and time but also will take into account the gradient, pavement type, urban obstacles, and many more. While the proposed approach offers promising benefits, it is crucial to acknowledge potential limitations, namely the complexity of incorporating a wide range of preferences that might raise some computational challenges, gathering and maintaining accurate and comprehensive data on cyclists, and prioritizing and weighting different cyclist preferences can be subjective and might need an overall consensus. The proposed approach holds the potential to contribute to navigation for cyclists by presenting safer, more enjoyable, and accessible cycling experiences for everyone, which may also contribute to sustainable transportation, improved urban planning, and a more engaged cycling community.

Keywords: Routing algorithms, Route optimization for bicycles, Multi-criteria routing, Cycling routes

Resumo

A pressão crescente para utilizar modos de transporte amigos do ambiente também exige o desenvolvimento de ferramentas de navegação avançadas, orientadas para estes tipos de veículos. Os ciclistas, por exemplo, têm preferências e necessidades diferentes que vão para além dos algoritmos de routing actuais que, muitas vezes, dão prioridade à distância e ao tempo, negligenciando a segurança, o conforto e a eficiência, conduzindo a percursos inseguros, desagradáveis ou ineficientes que podem desencorajar os ciclistas de utilizarem a bicicleta como meio de transporte principal. Para resolver este problema, esta dissertação propõe uma abordagem diferente ao planeamento de rotas que incorpora parâmetros de otimização para ciclistas e permite a seleção personalizada de rotas, abrindo caminho para que os ciclistas planeiem e encontrem rotas que não se concentrem apenas na distância e no tempo, mas que também tenham em conta o declive, o tipo de pavimento, os obstáculos urbanos, entre outros. Embora a abordagem proposta ofereça benefícios promissores, é crucial reconhecer as potenciais limitações, nomeadamente a complexidade da incorporação de uma vasta gama de preferências que podem levantar alguns desafios computacionais, a recolha e manutenção de dados exactos e abrangentes sobre os ciclistas e a atribuição de prioridades e ponderação às diferentes preferências dos ciclistas podem ser subjectivas e necessitar de um consenso geral. A abordagem proposta tem o potencial de contribuir para a navegação dos ciclistas, proporcionando experiências de ciclismo mais seguras, mais agradáveis e acessíveis a todos, o que pode também contribuir para transportes sustentáveis, um melhor planeamento urbano e uma comunidade ciclista mais interessada.

Keywords: Algoritmos de routing, Otimização de percursos para bicicletas, Optimização multicritério, Percursos de bicicleta

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"One important key to success is self-confidence.
An important key to self-confidence is preparation."

Arthur Ashe

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Abbreviations

AHP	Analytic Hierarchy Process
API	Application Programming Interface
CH	Contraction Hierarchies
DEM	Digital elevation model
EGM	Earth Gravitational Models
GIS	Geographic information System
GPS	Global Positioning System
HNR	Highway Node Routing
MCDM	Multi-criteria decision-making
ORS	Openrouteservice
OSM	OpenStreetMap
OSRM	Open Source Routing Machine
POI	Points of Interest
RAM	Random Access Memory
SRTM	Shuttle Radar Topography Mission
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UK	United Kingdom
VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje
WGS	World Geodetic System

Chapter 1

Introduction

In this chapter, we aim to contextualize and introduce our problem, section 1.1, show the motivation behind the pursuit of this thesis, section 1.2, present our objectives, section 1.3, and introduce the structure of the dissertation, section 1.4.

1.1 Context

Bicycles each day have become a choice for several people in order to flee from traffic and embark on a more sustainable and health-conscious alternative to traditional modes of transportation. Yet, navigating the urban network on two wheels can be daunting, between the intricate traffic, the complex road networks, and the inadequate infrastructure, that can transform a delightful journey into an uncomfortable and stressful experience.

Traditional routing algorithms are designed with a focus on motor vehicles, failing to capture the unique needs and preferences of cyclists, providing routes that are inefficient and unsafe, which can take out the pleasure of riding a bicycle. These routes often lead cyclists down high-traffic roads independently of existing dedicated lanes, which exposes them to potential collisions and incidents.

This challenge extends beyond safety [1], terrain is also an important factor in developing comfort and pleasure while riding a bicycle, where steep hills and rough surfaces can transform a pleasure ride into a grueling workout discouraging new users. Individual preferences also have an important role in establishing the best route for the cyclist, whether it's avoiding busy intersections and roundabouts or finding convenient rest stops, current algorithms lack this flexibility of generating the route based on the preferences and desires of the cyclists.

1.2 Motivation

This thesis aims to address the limitations of current routing algorithms for cyclists, developing an optimized approach to bicycle route planning, where the algorithm will prioritize safety over speed, comfort over distance, and personalized preferences over a one-size-fits-all solution in order to transform cycling from a daunting chore into a desirable and sustainable mode of transportation.

By addressing these limitations and developing an optimized approach to bicycle routing, we can pave a future for cyclists and generate routes where safety is a major factor, routes with dedicated infrastructure are going to be prioritized, which will minimize the exposure to traffic and factors like terrain and surface conditions will be in consideration while generating the route making comport also a priority.

Furthermore, the impact it can have extends far beyond a single individual, this can contribute to healthier communities by promoting physical activity and reducing the reliance on cars, leading to a healthier population [2], also encouraging cycling decreases traffic congestion and reliance on fossil fuels, fostering a more sustainable and environmentally friendly environment.

1.3 Objectives and Research Questions

Throughout this work, we seek to answer several questions from the following problem statement:

- Can an optimized route planning approach for cyclists, considering factors such as safety, comfort, and individual preferences besides distance and time, lead to an increase in adoption and satisfaction with cycling as a mode of transportation?

Subsequently, there are other questions that need to be answered, such as:

- **Safety:** Does the proposed approach reduce cyclists exposure to unsafe conditions?

- **Comfort:** Does the proposed approach, incorporating factors such as safety and gradient, effectively improve the cyclist's comfort and enjoyment?

- **Efficiency:** Does the proposed approach offer routes that are competitive in terms of travel time while simultaneously prioritizing safety and comfort?

Furthermore, we can also outline some objectives to be accomplished throughout this work.

- Develop a geographic database integrating data to be utilized for the optimization of the bicycle routes.

- Develop and implement a routing algorithm with the unique needs and preferences of cyclists.

- Compare the proposed approach to other routing algorithms and evaluate the benefits of the approach.

1.4 Document Structure

The document is divided into 6 main chapters, each addressing different aspects of the research. Chapter 1 starts by introducing the problem of the ineffectiveness of current cycling routes, outlining the motivation to develop a different approach, and presenting the objectives and research questions to be answered throughout. This chapter provides the foundation for understanding the scope and significance of the research. Chapter 2 dives into the existing knowledge, exploring various routing algorithms, engines, and data-gathering methods for cycling. It combines studies on safety, gradient considerations, and the current state of bicycle routing technologies. This comprehensive review sets the stage for identifying gaps and opportunities that the proposed approach aims to address. Chapter 3 outlines the methodology to be employed to develop and assess the proposed approach to optimizing routes for bicycle users. It details the data acquisition and integration processes, the development of the routing algorithm, and the criteria for route optimization. Chapter 4 evaluates the proposed routing optimization approach by analyzing its effectiveness, the use of the Analytic Hierarchy Process (AHP) provides valuable insights into the varying preferences of different cyclist profiles, such as commuters, sports enthusiasts, and leisure riders, highlighting the importance of various factors according to their preferences and needs. Chapter 5 presents the analysis and discussion of the results obtained from implementing the proposed approach. It includes case studies, comparative evaluations with existing routing solutions, and a detailed discussion on the performance and effectiveness of the optimized routes. This chapter provides critical insights into the practical applicability and benefits of the research. Finally, Chapter 6 draws the conclusions of the work done, summarizing the key findings and discussing the implications of the research. It also highlights the limitations of the current study and proposes directions for future work. This chapter provides a comprehensive overview of the outcomes and contributions of the dissertation.

Chapter 2

State of the Art

2.1 Algorithms

Routing algorithms have a crucial role in optimizing the paths for various modes of transportation, and in the context of bicycle routing, the choice to use a determined algorithm is very important, given the fact that understanding them and knowing how they work will provide a starting point to choose which ones would be beneficial, and that would provide the possibility to prioritize factors needed to create friendly routes for bicycle users.

Dijkstra's Algorithm [3] finds the shortest path between a given node and every other node in the graph and can also be used for finding the shortest paths from a single node to a single destination node by stopping the algorithm once the shortest path to the destination node has been determined. Works by successively improving an approximation d[v] to the shortest path length δ(s,v) from s to v, which is initially d[s]=0 and d[v]= ∞ for v$\neq$s. The algorithm maintains a priority queue of the vertices that haven't yet been processed. [1]

Bidirectional Search is a variant of Dijkstra's algorithm that simultaneously starts the forward and backward search until the collided node is found.[4] Combining both searches to obtain the route results. This algorithm is almost three times faster than the standard Dijkstra algorithm. [5]

A* Algorithm is a graph search and path search algorithm that is used in many fields of computer science due to its completeness, optimality, and optimal efficiency. Given a weighted graph, a source node, and a goal node, the algorithm finds the shortest path, with respect to the given weights, from the source to the goal.

Landmark A* is an extension of the A* algorithm that improves its efficiency by using landmarks, which are strategically placed nodes in the road network. Landmark A* builds a separate graph containing only the landmarks and their connecting edges, and it expands landmarks instead of regular nodes during the search process. This prioritization ensures that nodes that are more likely to lead to the goal are explored first, leading to faster search times. Additionally, Landmark A* uses a unique node ordering strategy that takes into account the distance of nodes from landmarks, ensuring that nodes closer to frequently visited areas are explored earlier. Overall,

[1] https://www.homepages.ucl.ac.uk/~ucahmto/math/2020/05/30/bidirectional-dijkstra.html

Landmark A* is a more efficient and robust algorithm for finding the shortest paths in large road networks compared to traditional A*. [6]

Contraction Hierarchies (CH) is a sophisticated algorithm designed to improve the efficiency of shortest path computations in large-scale road networks. The core idea of CH revolves around creating a multi-level hierarchical graph through a preprocessing step called node contraction. During this process, nodes (representing road intersections) are systematically removed from the graph one at a time, starting with the least important ones. As each node is removed, shortcuts are introduced to maintain the shortest paths within the network. This results in a simplified graph with significantly fewer nodes and edges, facilitating quicker navigation.[7]

Highway Node Routing (HNR) is another advanced algorithm aimed at accelerating shortest path computations by leveraging the natural hierarchy of road networks. HNR explicitly recognizes the hierarchical nature of road networks, where major roads (like highways) play a more critical role in long-distance travel compared to minor roads (like residential streets). The algorithm identifies a subset of important nodes, referred to as highway nodes, which typically include major intersections or critical junctions. These highway nodes form the backbone of the hierarchical structure within the network. [8]

2.2 Routing Engines

Routing engines are software applications that calculate the shortest path between two or more points on a network. There are two types of routing engines: static routing engines, which use pre-computed data to calculate routes, which makes them very fast, but they are not able to take into account real-time traffic conditions, and dynamic routing engines, which use real-time traffic data to update routes in real-time, meaning that they are more accurate than the static routing engines, but are more computationally expensive.

Table 2.1: Static vs Dynamic Routing Engines

Feature	Static Routing Engines	Dynamic Routing Engines
Data used	Pre-computed	Real-time traffic
Accuracy	Lower	Higher
Performance	Faster	Slower
Cost	Lower	Slower

2.2.1 Static Routing Engines

OSRM is an open-source routing engine that is known for its high performance and low latency because it uses pre-computed data to calculate routes that provide a fast performance for short and medium-distance routes. However, it might not be the best choice for applications that require accurate real-time routing. [2]

[2]https://github.com/Project-OSRM/osrm-backend/blob/master/README.md

pgRouting is a PostgreSQL extension that provides routing functionality in a relational database, allowing the calculation routes directly within PostgreSQL, being very helpful in applications that need integration with other database operations. pgRouting is very flexible and can be used and customized to support different routing algorithms and use cases. [3]

2.2.2 Dynamic Routing Engines

Graphhopper is another open-source routing engine that is popular for its flexibility and support for various transportation modes, it also has a variety of routing options from fast to shortest paths and scenic paths, although not as OSRM for short-distance routing it still presents a good performance and can handle longer routes more efficiently.[4]

Valhalla is a new open-source routing engine that is known for its unique approach to routing, by using a tiled hierarchical graph structure that allows it to be more efficient in large-scale routing. Valhalla also supports time-aware routing, meaning that it can take into account departure and arrival times as well as real-time traffic data.[5]

Openrouteservice or ORS is a commercial routing service that uses a combination of open-source routing engines, including OSRM and Graphhopper. It offers a variety of features, including elevation querying, POI search, and vehicle routing problem solver. Also, it is very easy to use and can be integrated with other applications.[6]

2.2.3 Comparing Routing Engines

The table below 2.2 has an overview of some of the profiles, APIs, and attributes relevant to this work and will help choose the most suitable routing engine for the work. The more stars, the better, meaning that a 5-star attribute is the best and a 1-star attribute is the worst compared to others.

The attributes measured are activity, measuring commit frequency, issue responses or fixes, and community involvement, performance, although it is a little subjective on the query or request, RAM requirements, how much RAM is needed to build and load the graph, customizability, which should reflect the ease with which profiles can be customized, flexibility, denoting the capability of the routing engine to customize the weights per request.[7]

[3] https://pgrouting.org/
[4] https://www.graphhopper.com/
[5] https://github.com/valhalla/valhalla
[6] https://openrouteservice.org/
[7] https://gis-ops.com/open-source-routing-engines-and-algorithms-an-overview/

Table 2.2: Comparison between routing engines [7]

	OSRM	Graphhopper	Valhalla	Openrouteservice	pgRouting
Profiles Bicycle	Yes	Yes	Yes	Yes	Yes
API Routing	Yes	Yes	Yes	Yes	Yes
Isochrones	No	Yes	Yes	Yes	Yes
Matrix	Yes	No	Yes	Yes	Yes
Map Matching	Yes	Yes	Yes	No	No
Optimization	No	No	Yes	No	Yes
Features Elevation	No	Yes	Yes	Yes	Yes
Activity	***	*****	*****	*	****
Performance	*****	****	***	****	**
RAM requirements	*	***	****	*	*****
Customizability	***	***	**	*	****
Flexibility	*	***	****	*	*****

2.2.4 Choosing a Routing Engine

Choosing the right routing engine is important since it will impact the work to be done. Different routing engines provide various functionalities and optimization algorithms, so selecting the right one will ensure that it can handle specific criteria like avoiding certain roads and considering individual needs, another factor to take into account is the ability of the routing engine to seamlessly integrate the data that is going to be used. The compatibility with this data will guarantee its efficiency in data processing and route creation. Choosing an inadequate routing engine might compromise the goals and limit the approach's effectiveness.

After a thorough comparison of the various routing engines, including OSRM, Graphhopper, Valhalla, Openrouteservice, and pgRouting, we have decided to use pgRouting.

One of the primary reasons for choosing pgRouting is its seamless integration with PostGIS, which allows for efficient handling of spatial data. pgRouting supports a wide range of geospatial data types and functions, making it ideal for integrating data. This compatibility ensures that we can efficiently process and generate routes that meet the specific needs of cyclists.

pgRouting also offers high customizability and flexibility, which are critical aspects of our work, enabling us to tailor the routing algorithm to prioritize safety, effort, and other important criteria identified in our research, helping to align with the unique requirements of the cyclists in Porto.

Although the performance of pgRouting is not the best, [7], it is sufficient for our needs, particularly when considering the trade-offs between performance and the ability to customize and integrate various data sources. Given these considerations, pgRouting stands out as the most suitable choice for this work.

2.3 Multi-criteria Routing

Multi-criteria routing is different from the traditional routing algorithms that commonly focus only on the traveling time and distance. As the name indicates, multi-criteria routing considers multiple factors to determine the best route between the source and destination. It can take into account more factors beyond the distance and travel time, such as, for example, the financial cost, safety, traffic congestion, and conditions of the road, among others.

This multi-criteria approach has been addressed in [9], where they implemented this approach taking into account several factors, including travel time, elevation, number of stops, and also preference for scenic routes, proving the effectiveness of multi-criteria routing in identifying good routes, in the challenging city of Prague.

2.3.1 Multi-criteria Decision-making

Multi-criteria decision-making (MCDM) is a branch of decision science dealing with making decisions when there are multiple and conflicting criteria, helping to choose between the alternative courses of actions with a systematic and rational way of evaluating each alternative. There are several methods available, each with its strengths and weaknesses, shown in table 2.3.

[7] https://gis-ops.com/open-source-routing-engines-and-algorithms-an-overview/

Table 2.3: MCDM methods, which are widely studied and applied in various fields. [10]

Method	Acronym	Description
Analytic Hierarchy Process	AHP	A decision-making technique that helps structure complex problems into a hierarchy of criteria and alternatives, and then evaluates them based on pairwise comparisons using numerical scores. AHP is useful when there are multiple criteria to consider, and when the decision maker wants to incorporate subjective judgments into the decision-making process.
Technique for Order of Preference by Similarity to Ideal Solution	TOPSIS	A method that ranks alternatives based on their similarity to the ideal solution and dissimilarity to the worst solution, using distance measures such as Euclidean or Manhattan distance. TOPSIS is useful when there are multiple criteria to consider, and when the decision maker has a clear idea of what constitutes the best and worst solutions.
VlseKriterijumska Optimizacija I Kompromisno Resenje	VIKOR	A method that combines the concepts of compromise programming and outranking relations to determine the best alternative based on both the overall performance and the distance from the ideal solution. VIKOR is useful when there are multiple criteria to consider, and when the decision-maker wants to balance overall performance with the differences between the best and worst alternatives.

The choice of which MCDM method to use depends on the problem, considering factors such as the number of criteria, the type of criteria, the preferences of the decision-makers, and the data available.

2.3.2 Weights and Priorities

The study of parameters to use in MCDM routing is important, and defining their weights and priorities will impact decision-making in creating an optimal route distribution. The existing literature on routing parameters has focused primarily on routing for cars, giving a general understanding of the importance of the weights and priorities as the case study of [11], where they define weights for distance, cost, congestion, and risk and found that the combination of the MCDM and the Dijkstra's algorithm proved to be a viable method to find the optimal route in a network, showing that the system is able to handle the variety of parameters and is able to take into account their priority levels for each parameter.

2.4 Data Gathering

With the world procuring a more sustainable way of living, bicycle routing algorithms and routing engines have been gaining more significance over the years by promoting a sustainable way of transportation. Bicycle routing also has a crucial role in improving the road network in order to give cyclists of all levels of experience the opportunity to choose this sustainable mobility.

Researchers have been exploring various ways of enhancing the efficiency and accuracy of bicycle routing and each year, we see a more profound engagement throughout the community in retrieving data from cyclist's routes using various methods, such as GPS, crowdsource, and others. This study [12], where they gathered empirical searches on this area over the years, shows the more common ways that routes are being gathered. In figure 2.1, we can see a graph showcasing the growth of empirical searches for bicycle routes that were published and which are the predominant ways of retrieving this information.

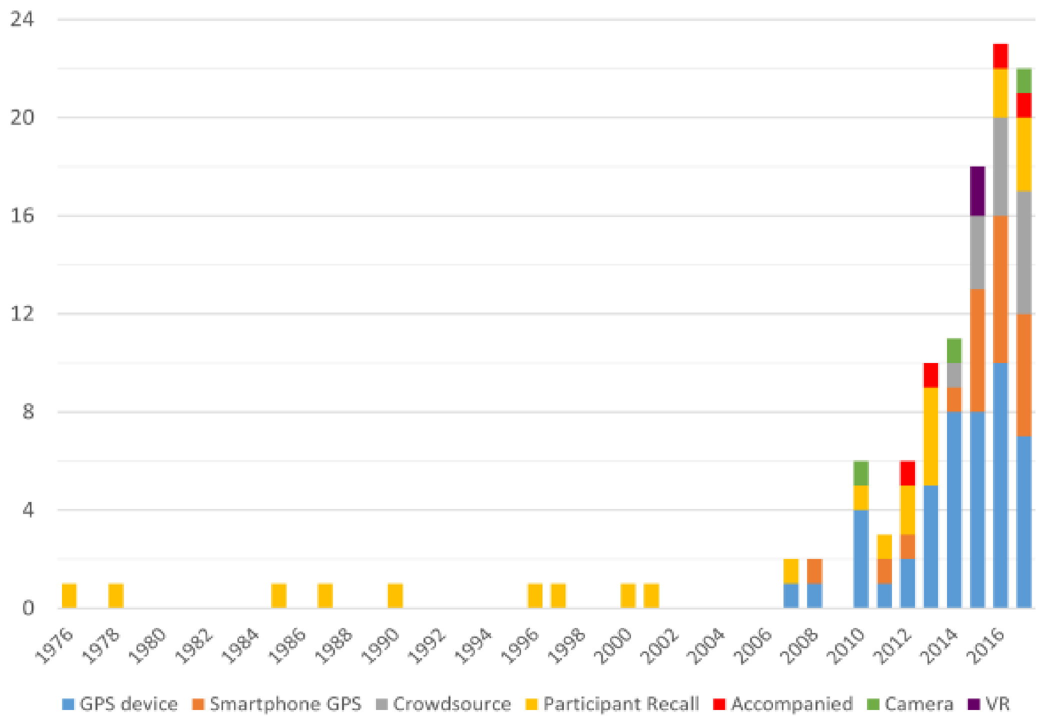


Figure 2.1: Revealed preference bicycle route choice publications for bicycle routes [12]

In figure 2.1, we can see a histogram graph that shows the growth of empirical searches for bicycle routes. As we can see, crowdsourcing and GPS data have emerged as a valuable source of information for bicycle routing applications. User-generated data on cycling experiences and route conditions can be used to improve the accuracy and coverage of routing data. These efforts are beneficial, particularly in areas where there is only outdated or limited information.

2.5 Online route planners

Over the years, many online route planners have developed routing for cycling purposes. Google Maps [8] supports bicycle route planning, but only in some areas. However, it does not allow cyclists to set up their own preferences. OpenTripPlanner [9], which is an open-source multimodal trip planner, has a mode of bicycle route planning where users can choose their ratio of quickness to flatness to bike friendliness, giving users a set of preferences to choose from. Cyclestreets [10] is also another cycle journey planner that is only employed in the UK, which returns three routes: the fastest, the quietest, and the balance between both.

Table 2.4: Online route planners and some of their features. [8] [9] [10]

Features	**Google Maps**	**OpenTripPlanner**	**CycleStreets**
Elevation data	Yes	Yes	Yes
Bike path and lane information	Yes	Yes	Yes
Bike speed and incline recommendations	No	Yes	No
Multimodal routing	No	Yes	No
Real-time data integration	Limited	Limited	Yes

2.6 Safety

Safety is an important factor for bicycle users, as it directly impacts their well-being and provides viability of cycling as a means of transportation. Articles such as [13] and [14] provide an overview of various factors that contribute to the safety of bicycle users. Furthermore, [13] presents important information regarding different route types and injuries that occurred on each of them.

[8] https://www.google.com/maps/
[9] https://www.opentripplanner.org/
[10] https://www.cyclestreets.org/

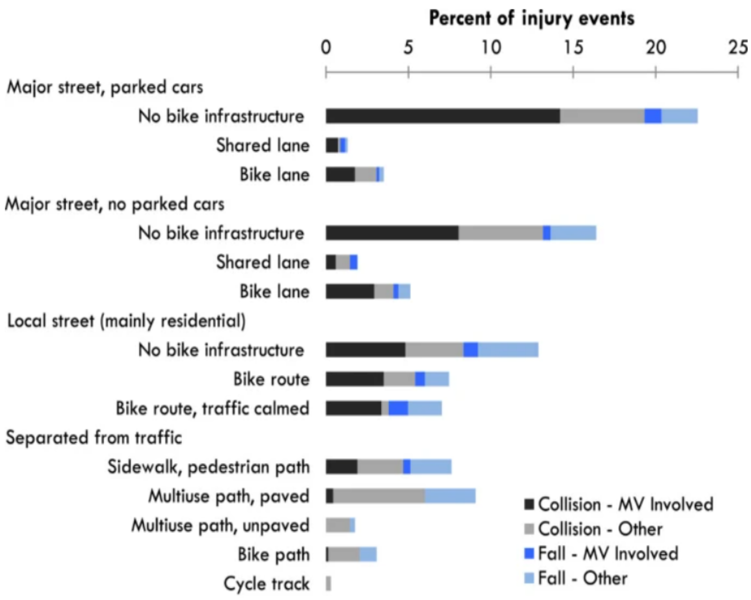


Figure 2.2: Route types where injury events occurred, stratified by broad crash circumstances. [13]

As we can see from figure 2.2, the dominant routes where crashes occurred were on major streets with no bicycle infrastructure (with or without parked cars, 22.5 % and 16.4% respectively), residential streets with no bike infrastructure (12.9%), and off-street multi-use paths (9.1%) and motor vehicle involvement in collisions and falls featured most prominently on major streets with parked cars, and almost not at all on routes separated from traffic.[13]

2.7 Slope Criteria

The slope is also another crucial factor to take into account when talking about bicycle routing, which influences the difficulty of the route, particularly for conventional bicycles.

Table 2.5: Slope criteria for conventional bicycles. [15]

Source	Slope	Criteria/Description
[16]	0 to 2%	No limit
	2% to 4%	Up to 4 km
	4% to 5%	Up to 2 km
	5% to 7%	120 m to 240 m
	7% to 10%	30 m to 90 m
	more than 10%	15 m
[17]	0 to 3%	For cycle tracks, a maximum slope of 3% is recommended.
	3 to 5%	3% can rise to 5% over a distance of up to 100 m.
	5 to 7%	Where it is unavoidable, a slope of up to 7% over a distance of no more than 30 m is acceptable.
	>7%	In some circumstances, slopes steeper than 7% over short distances on a cycle route may be preferable to failing to provide the route at all.
[18, 19]	0 to 3%	3% is the desirable maximum slope for use on cycling paths.
	3 to 5%	Slope to a maximum of about 5% and providing short flatter sections (20 m long) at regular intervals to give cyclists traveling, both uphill and downhill, some relief from the slope.
	>5%	Slope steeper than 5% should not be provided unless it is unavoidable.
	Avoid	Slope greater than 10% over 50 m with horizontal curves or a slope of 12% over 50 m on a straight path.
[20]	<4%	Topography is not a limiting factor.
	4 to 8%	Topography does become a significant constraint.
	>8%	Cyclists generally avoid steep uphill and downhill slopes.

The table above 2.5 outlines the recommended slope for conventional bicycles based on several sources Other studies compared the speed of conventional and electrical bicycles on different slope percentages, on slopes above 9%, there was a slower speed of about 42.7% in comparison with a gradient between 0 to 1% and for electrical bicycles of about 32.3%. [21]

2.8 OpenStreetMap

OpenStreetMap (OSM) is a collaborative, open-source platform that provides detailed global map data freely and is available to everyone. Its success is derived from citizens mapping and collecting data and information about the city they live in. [22]

Some of the strengths of OSM for Cycling are the extensive coverage of cycling infrastructures worldwide [23], which include bicycle lanes, paths, and traffic features, there are continuous updates by contributors in order to ensure the data reflects current infrastructure, tags like surface offer valuable information about the terrain suitability, present of elevation data.

Other layers focused on bicycles have been created on top of OSM such as OpenCycleMap and CyclOSM

2.8.1 OpenCycleMap

OpenCycleMap is an OSM layer like the standard, but its purpose is only to show information that is useful for cyclists, featuring dedicated cycle tracks and lanes, parking for bicycles, proposed bike routes, and points of interest specifically for cyclists.[11]

2.8.2 CyclOSM

CyclOSM is a new cycle-oriented render, and contrary to OpenCycleMap, its rendering is free and open-source software that aims to be more complete, taking into account a wider diversity of cycling habits. Also, it is designed to consider diverse cycling profiles and preferences through lateralized lane display and emphasis on infrastructure quality. [12]

Moreover, while OSM provides extensive global cycling infrastructure data, OpenCycleMap offers a cyclist-focused layer highlighting dedicated lanes and points of interest, and CyclOSM provides a newer open-source rendering for diverse cycling needs. The integration of data from all these sources will be strategic in order to build a good base to create safe and comfortable routes for bicycles.

2.8.3 Map Features

OSM map features are created using tags that are attached to its basic data structures.[13] [14] These tags are key-value pairs that help describe a geographic attribute of the feature that is being shown in that specific node, way, or relation. For this work, we will mainly be looking for features on the maps that are in the table 2.6.

[11] https://wiki.openstreetmap.org/wiki/OpenCycleMap
[12] https://wiki.openstreetmap.org/wiki/CyclOSM
[13] https://wiki.openstreetmap.org/wiki/Map_features
[14] https://download.geofabrik.de/osm-data-in-gis-formats-free.pdf

Table 2.6: OSM Map Features [13] [14]

Key	**Value**	**Description**
highway	cycleway	For designated cycleways.
cycleway	lane	Route that lies within the roadway
cycleway	opposite	Used on ways with oneway=yes where it is legally permitted to cycle in both directions. Used together with oneway:bicycle=no.
cycleway	opposite_lane	Used on ways with oneway=yes that have a cycling lane going the opposite direction of normal traffic flow (a "contraflow" lane). Used together with oneway:bicycle=no.
cycleway	track	Separated from the traffic
cycleway	opossite_track	Separated from the traffic but going against its flow
cycleway	shared_busway	There is a bus lane that cyclists are permitted to use.
cycleway	shared_lane	Cyclists share a lane with motor vehicles, but there are markings indicating that they should share the lane with motorists. In some places these markings are known as "sharrows" ('sharing arrows') and this is the tag to use for those.
cycleway	opposite_share_busway	Used on ways with oneway=yes that have a bus lane that cyclists are also permitted to use, and which go in the opposite direction to normal traffic flow (a "contraflow" bus lane). Used together with oneway:bicycle=no.
bicycle_road	Yes	A bicycle road is a road designated for bicycles. If residential streets get the status of bicycle roads, normally, by special signs, motor traffic is admitted with limited speed, often only for residents
Incline	Number % | ° | up | down	Incline steepness as percents ("5%") or degrees ("20°"). Positive/negative values indicate movement upward/downwards in the direction of the way.
junction	roundabout	
smothness	excellent | good | intermediate | bad | very_bad | horrible | very_horrible | impassable	Specifies the physical usability of a way for wheeled vehicles due to surface regularity/flatness.

Key	**Value**	**Description**
Surface	paved | unpaved | asphalt | concrete | paving_stones | sett | cobblestone | metal | wood | compacted | fine_gravel | gravel | pebblestone | plastic | grass_paver | grass | dirt | earth | mud | sand | ground	Information about the physical surface of roads/footpaths and some other features, particularly regarding material composition and/or structure.
route	bicycle	Cycle routes or bicycles route are named, numbered or otherwise signed. May go along roads, trails or dedicated cycle paths
ele	number	Elevation (also known as altitude or height) above mean sea level in meter, based on geoid model EGM 96 which is used by WGS 84 (GPS).
amenity	bicycle_parking	Parking for bicycles
amenity	bicycle_repair_station	General tools for self-service bicycle repairs, usually on the roadside; no service
amenity	bicycle_wash	Clean a bicycle
amenity	bicycle_rental	Rent a bicycle
amenity	compressed_air	A device to inflate tires/tyres (e.g. motorcar, bicycle)

Chapter 3

Solution for routing Optimization

This chapter lays out the procedures and strategies chosen to address the challenge of route optimization for cyclists and serves as a blueprint for our research.

3.1 Data Acquisition and Integration

This section delves into the methodologies and sources involved in the process of acquiring and integrating data from various datasets, focusing on how these datasets contribute to a better understanding and enhancement of bicycle mobility within urban environments.

At the beginning of the work, the data collected was for the whole country of Portugal, but due to performance issues and long query times, it was reduced to the district of Porto.

3.1.1 Data Sources

The first step in data acquisition is identifying and accessing relevant data sources.

3.1.1.1 Geospatial Data

Geographic information System (GIS) data provides detailed spatial information about the infrastructure, road networks, cycle paths and elevation, this data is important in order to understand the potential routes and to know what physical environment cyclists navigate in.

The overall road infrastructure was obtained from OpenStreetMap [1], and the elevation of the terrain from *NASA Shuttle Radar Topography Mission Global 1 arc second V003* (SRTM.v3) [2], which has a resolution of $\sim$ 30 meters and is one of the most preferred DEMs [24], and in consideration to Portugal its completeness is excellent [25].

[1] https://download.geofabrik.de/europe/portugal.html

[2] https://search.earthdata.nasa.gov/search/granules?p=C2763266360-LPCLOUD

3.1.2 Data Integration and Database

Data integration is a pivotal step in developing routing algorithms, aggregating the various data sources gathered previously and unifying them into a system that can be efficiently queried and analyzed. For this, we leveraged the powerful capabilities of PostGIS and QGIS to manage and visualize our geospatial data.

3.1.2.1 PostGIS and QGIS

PostGIS is an extension of the PostgreSQL relational database system that adds support for geographic objects, transforming PostgreSQL into spatial data storage, enabling the storage of various geospatial data types such as points, lines, and polygons, data essential to represent roads and geographic elements. Moreover, PostGIS already has a range of spatial functions that help query and analyze geographic data.

QGIS offers a robust platform for visualizing spatial data in various formats, elevation profiles, cycling routes, and other relevant data. Also, QGIS seamlessly connects to PostGIS databases, which allows the manipulation and query of the data stored in the database, and any change in the database is immediately reflected in QGIS, providing a dynamic and up-to-date view of the data.

Furthermore, QGIS has a plugin for pgRouting, a routing engine that will be used to create and visualize the routes.

In order to create a PostGIS database, extensions were added using the PSQL terminal from pgAdmin 4, a management tool for PostgreSQL.

```
CREATE EXTENSION IF NOT EXISTS postgis;
CREATE EXTENSION IF NOT EXISTS postgis_raster;
CREATE EXTENSION IF NOT EXISTS pgrouting;
```

With this we enable the PostGIS database and pgRouting routing engine that is will be used later.

3.1.2.2 Data preprocessing

Before adding the data to the database, cleaning and validation processes were performed in order to ensure consistency and usability for the bicycle routes.

Road Network First things first, taking out unnecessary information, which are roads that bicycles cannot ride on, like motorways, and other irrelevant features like airways, waterways, construction plants, and others, so for this, a filter was made.

```
portugal_osm_filtered <- portugal_osm %>%
  filter(highway %in% c('primary', 'primary_link', 'secondary', 'secondary_link',
                        'tertiary', 'tertiary_link', 'trunk', 'trunk_link',
```

```
                    'residential', 'cycleway', 'living_street',
                    'unclassified', 'footway', 'pedestrian',
                    'track', 'path', 'steps'))
```

After filtering by the road classification from OSM, roads on which tags like *bicycle* = *no* were present were also eliminated since this meant that no bicycle could ride on that road.

Figure 3.1: Before filtering the network

Figure 3.2: After filtering the network

Using this filter, we cleaned a big part of the road network, although some roads classified as footways or pedestrians could be filtered, there wasn't a common ground to eliminate them without taking out ones on which cyclists could ride, so it was decided to maintain all of them.

Another problem encountered when visualizing and analyzing the data on QGIS was that not all roads were broken on the nodes of intersections. To overcome this problem we used *stplanr::rnet_breakup_vertices(network)* [26], which breaks up a single linestrings into multiple linestring at points where vertices from other linestrings in the network intersect with vertices in the original linestring [3].

[3] https://www.rdocumentation.org/packages/stplanr/versions/0.5.2/topics/rnet_breakup_vertices

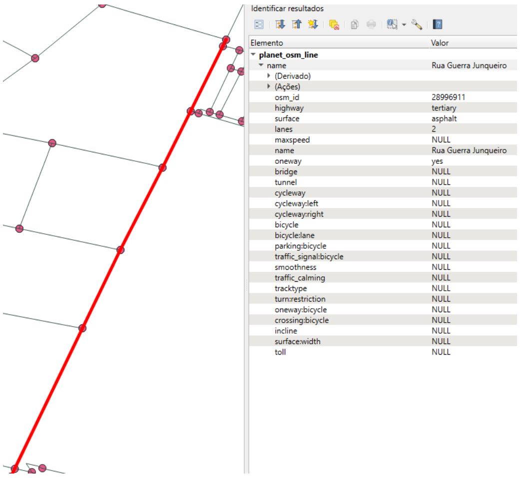


Figure 3.3: Before rnet_breakup_vertices

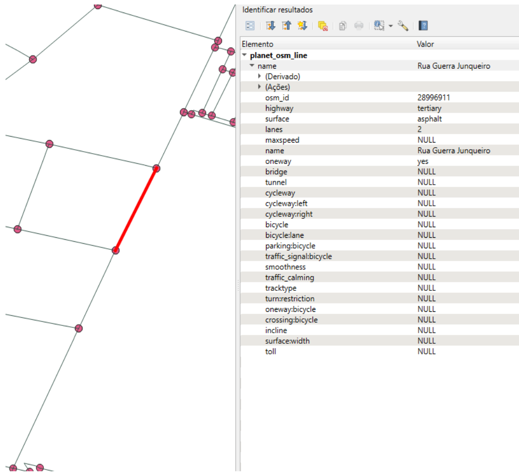


Figure 3.4: After rnet_breakup_vertices

By preprocessing and filtering the data to remove non-cyclable roads and ensure proper network segmentation, we create a clean and accurate dataset that is ready for routing analysis and visualization in QGIS.

Digital Elevation Model Data Provides detailed information about the elevation of the terrain, which is essential to assess the slopes and effort required to ride the various routes. Moreover, incorporating elevation data into the routing algorithm enables more accurate and practical route recommendations, taking into account downhills and uphills.

The SRTM.v3, as already discussed in 3.1.1.1, was used, and to incorporate it into the database, first, we had to join all raster tiles that cover the region of Portugal, creating a new elevation raster to make it easier for querying and elevation analyzes.

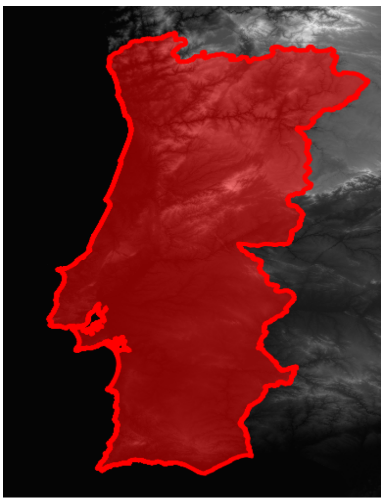


Figure 3.5: SRTM.v3 elevation raster

3.2 Data Structure

In this section, we delve into the data structures used in our work, focusing on two primary structures for modeling the road network of Porto for route optimization: `porto_district` and `porto_district_vertices_pgr`. These structures are fundamental for storing the graph representation of the city's road network, which is essential for implementing the routing algorithms.

3.2.1 porto_district Table

The `porto_district` table represents the edges in the road network graph. Each edge denotes a road segment connecting two nodes (intersections or significant points). This table includes various attributes that are critical for routing, such as the length, cost, and type of road surface.

Below is an overview of the main columns in the `porto_district` table:

- **id**: Unique identifier for each edge.
- **geom**: Geometry of the edge represented in WKT (Well-Known Text) format.
- **fid**: Feature identifier.
- **osm_id**: OpenStreetMap identifier.
- **name**: Name of the road.
- **highway**: Type of road (e.g., residential, primary).
- **length**: Length of the road segment.
- **surface**: Type of road surface (e.g., asphalt, paved).
- **slope**: Slope of the road segment.
- **cycleway**: Indicates if the road has a cycleway.
- **other_tags**: Additional tags stored as key-value pairs using the PostgreSQL `hstore` extension. This column can include various optional attributes such as speed limits, lane information, or any other metadata relevant to the road segment.
- **cost**: Default cost associated with traversing the segment.
- **rev_cost**: Default reverse cost (for traversing in the opposite direction).
- **costcommuter**: Cost for commuter profile.
- **rev_costcommuter**: Reverse cost for commuter profile.
- **costsports**: Cost for sports profile.

- **rev_costsports**: Reverse cost for sports profile.
- **costleisure**: Cost for leisure profile.
- **rev_costleisure**: Reverse cost for leisure profile.

3.2.2 porto_district_vertices_pgr Table

The `porto_district_vertices_pgr` table represents the nodes in the road network graph. Each node signifies an intersection or a significant point in the road network. This table includes coordinates and elevation, which are crucial for calculating distances and optimizing routes based on elevation changes.

Below is an overview of the main columns in the `porto_district_vertices_pgr` table:

- **id**: Unique identifier for each node.
- **longitude**: Longitude coordinate of the node.
- **latitude**: Latitude coordinate of the node.
- **elevation**: Elevation of the node above sea level.

These data structures are integral for the database schema, enabling efficient storage and retrieval of road network information.

3.3 Road Network Topology and Elevation Integration

This section focuses on creating a foundation for the bicycle routing algorithm by establishing a road network topology and incorporating elevation data into each node to calculate the gradient of each road segment.

3.3.1 Road Network Topology

A road network topology represents the structural layout of roads in terms of nodes (intersections) and edges (road segments). pgRouting, an extension of PostGIS that adds routing and network analysis capabilities, was used.

Using *pgr_createTopology*, a function that generates a graph where nodes represent intersections and edges represent the road segments is essential to generate a topology from the road data. For the purpose of creating the topology, two columns needed to be added to the road data to store the source and target nodes, beginning and end of a road segment.[27]

```
ALTER TABLE "porto_district" ADD COLUMN "source" integer;
ALTER TABLE "porto_district" ADD COLUMN "target" integer;
SELECT pgr_createTopology('porto_district', 0.00001, 'geom', 'fid');
```

After the topology was created another table was added to the database in order to store necessary information as elevation to nodes for later use in calculating the gradient of the road segments. [27]

```
CREATE TABLE porto_district_node AS
    SELECT row_number() OVER (ORDER BY foo.p)::integer AS id,
    foo.p AS geom
    FROM (
        SELECT DISTINCT "source" AS p FROM "porto_district"
        UNION
        SELECT DISTINCT "target" AS p FROM "porto_district"
        ) foo
    GROUP BY foo.p;
```

3.3.2 Elevation Integration

In order to integrate the elevation data into the road network, we added to every node its relative elevation. With this, we can later calculate the slope and reverse slope through the source and target from the road segments, which represent these nodes that now have information about their elevation.

```
ALTER TABLE porto_district_vertices_pgr ADD COLUMN elev float8;

CREATE TABLE elevation_vertices AS SELECT ST_Value(srtm.rast, pt.the_geom) AS
    elev, pt.id
    FROM elevation srtm
    JOIN porto_district_vertices_pgr pt
    ON ST_Intersects(pt.the_geom, ST_ConvexHull(srtm.rast));

UPDATE porto_district_vertices_pgr pt
    SET elev = elevation_vertices.elev
    FROM elevation_vertices
    WHERE pt.id = elevation_vertices.id;
```

3.3.2.1 Slope Calculation

Slope calculation is, if not the most important, one of the most important parts of bicycle routing. Calculating the slope involves determining the difference in elevation between the source and target nodes, and vice versa for the reverse slope, over the distance of each road segment. This section details the steps to calculate the slope using the elevation data integrated into our road network.

$$S = \frac{\Delta h}{Length} * 100 \tag{3.1}$$

$\Delta h = h_{target} - h_{source}$: The difference in elevation between the source and target nodes of a road segment.

```
ALTER TABLE porto_district ADD COLUMN slope_source_to_target float;
ALTER TABLE porto_district ADD COLUMN slope_target_to_source float;

CREATE TABLE slope AS
    SELECT (t.elev-s.elev)/pt.length_meters*100 AS slope, pt.fid
    FROM porto_district pt
    JOIN porto_district_vertices_pgr s ON pt.source = s.id
    JOIN porto_district_vertices_pgr t ON pt.target = t.id

Update porto_district pt set slope_source_to_target = d.slope FROM slope d
    WHERE pt.fid = d.fid

Update porto_district set slope_target_to_source = slope_source_to_target * -1
```

After adding the slope and reverse slope to each road segment of the road network, some problems were encountered, which made some road segments have an unreal slope %, and since the steepest road in the world has a 34.8% gradient [4], we made any road with a slope above 30 % to have a slope of 30%. Further investigation showed that the majority of these roads were road segments with a small length, and the majority were tracks and paths in areas with mountains, mainly due to the resolution of the DEM being $\sim$ 30 meters, the source and target nodes were in different elevation tiles, which made them have the unreal slope %. The roads that had an unreal slope % represented 2.9% of the network.

[4]https://www.guinnessworldrecords.com/news/2020/4/baldwin-street-in-new-zealand-reinstated-as-the-worlds-steepest-street-614287

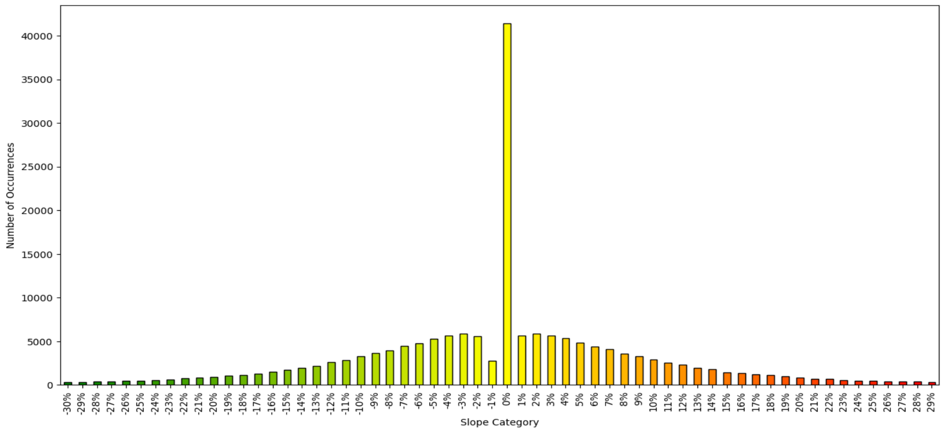


Figure 3.6: Distribution of slopes in the district of Porto.

The bar chart in figure 3.6 illustrates the distribution of slope categories from -30% to 30%, with each bar representing a 1% increment. The x-axis shows the slope categories, while the y-axis indicates the number of occurrences for each category. A prominent feature of the chart is the significantly high number of occurrences at the 0% slope category, suggesting a large portion of the data represents flat terrain. The distribution is symmetrical around the 0% slope, with similar counts for negative and positive slopes of the same magnitude, and the number of occurrences decreases as the slope values move away from zero in both directions. This indicates that steeper slopes are less common. The gradient color scheme, transitioning from green for negative slopes to yellow around zero and red for positive slopes, aids in the visual differentiation of the slope categories. The extreme slope categories, both negative and positive, have minimal counts, highlighting their rarity in the district of Porto.

3.4 Dijkstra's Algorithm and Directed Road Network

In this section, we delve into the modifications to the cost and reverse cost on the road network in order to ensure its accuracy in routing and assembling a directed road network.

3.4.1 Dijkstra's Algorithm

Dijkstra's algorithm, a well-established pathfinding algorithm used to find the shortest path between two nodes in a weighted graph, is known for its efficiency and accuracy. This makes Dijkstra's algorithm suitable for our needs due to its ability to handle weighted graphs, making it ideal for considering various factors such as ones in section 3.6. Dijkstra's algorithm can handle directed graphs, and since our network considers directionality, a reverse cost is assigned to every road segment, which represents the cost of the traversal of the edge in the opposite direction. [28, 29]

3.4.2 Directed Road Network

In order to accurately model the real-world road network, we employed a directed graph where edges have both cost and reverse_cost attributes, representing the cost associated with traversing a particular road segment in either way. To do this, we made adjustments to the reverse cost for streets that are one-way and roundabouts or junctions.

```
    UPDATE porto_district
        SET rev_cost = rev_cost + 1000000
        WHERE other_tags ? 'junction' IS TRUE;

    UPDATE porto_district
        SET rev_cost = rev_cost + 1000000
        WHERE other_tags -> 'oneway' = 'yes';
```

By increasing the reverse cost by 1,000,000, we ensure that the routes won't go against the designated flow of one-way streets and junctions, aligning this way the road network with real-world traffic regulations and enhancing route safety.

These updates ensure that the directed road network accurately reflects constraints and conditions cyclists might encounter, leading to safer and more realistic route recommendations, and by combining Dijkstra's algorithm with these targeted modifications to the road network, our routing model can efficiently generate optimized routes that do not only prioritize cyclist safety but also adhere to traffic rules, while also considering the other factors.

3.5 Creating and visualizing routes

In order to create and visualize the routes, we use the PostGIS extension pgRouting and QGIS, respectively. The following SQL query utilizes the pgr_dijkstra function to compute the shortest path between two nodes in the road network.

```
select seq, node, edge, rd.fid, prt.cost, rev_cost, st_astext(geom) as geom
    from pgr_dijkstra(
        'select fid as id, source, target, cost, rev_cost from porto_district',
        79841, 116925,
        directed := true) as prt
    join porto_district rd on prt.edge = rd.fid;
```

Once the query is executed, the results can be visualized using QGIS, which displays the route on the map, highlighting the optimal path between the specified nodes based on the defined cost parameters. This visualization allows for an intuitive understanding of the route's characteristics and assists in further analysis and evaluation of the routing algorithm's performance, regarding each route.

Additionally, it is possible to perform the entire process within QGIS using the pgRouting Layer plugin. This plugin accepts the same arguments as the SQL query above, and after connecting the database to QGIS, the plugin enables a faster and easier way to create and visualize routes, allowing to directly select nodes on the map and create a route between them, as shown in figure 3.7.

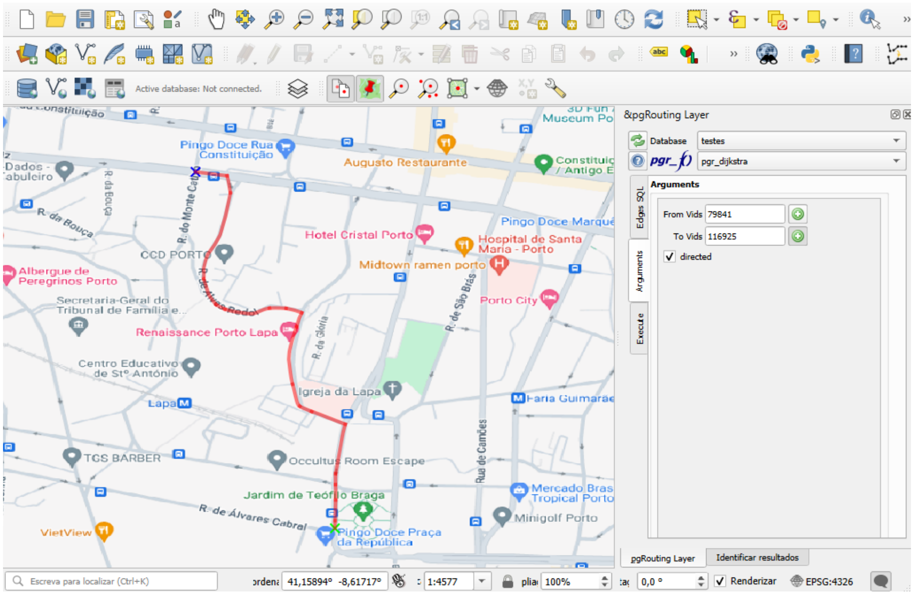


Figure 3.7: Simple route example from R. de Egas Moniz to Jardim de Teófilo Braga

3.6 Cost and Weight Functions

This section delves into the heart of our bicycle routing algorithm, considering the various factors that impact the ride for cyclists. These factors play a crucial role in tailoring cyclists' specific needs and preferences. Unlike motor vehicles, bicycles are more sensitive to the physical terrain and personal ride differences, and by carefully quantifying and assigning values to these weights and parameters, we prioritize certain factors like distance, speed, elevation, safety, surface type, and overall effort.

The following subsections will explore each of these factors in detail and explain how they are integrated into the algorithm. Plots on the municipal of Porto will be shown to represent the factor assignment, making it easier to understand.

3.6.1 Speed

The speed factor is returned in seconds and corresponds to the time that it takes to traverse a road segment. We used a base velocity of 15 km/h with an acceleration of 1, in other words, the velocity is constant to calculate it.

$$f_{speed}(velocity, length) = \frac{length\,[m]}{velocity\,[^{km}/_{h}]/3.6} \tag{3.2}$$

This will be our base for calculating the costs of every other factor corresponding to the t variable.

$$C_{speed} = f_{speed}(velocity, length) = t(s) \tag{3.3}$$

3.6.2 Cycleway

The function $f_{cycleway}(x)$ identifies and prioritizes pathways dedicated to cyclists, optimizing route safety and comfort. These ways are specially designed for bicycle traffic, providing a protected and more enjoyable riding experience.

$$f_{cycleway}(x) = \begin{cases} 0.6 & \text{if } x \text{ is a cycleway,} \\ 1 & \text{if } x \text{ is not a cycleway} \end{cases} \tag{3.4}$$

The cycleway factor is a simple yet effective way to prioritize routes that include dedicated paths for cyclists. The cycleway function assigns a 0.6 factor to pathways that are classified as a cycleway and, if not, assigns a factor of 1.

For cyclists who prioritize safety and comfort, routes with more cycleway segments are more appealing, hence, prioritizing them is a crucial factor in optimal routes for cyclists.

The cost function of the cycleway factor is presented in the equation below, in which the cost of traverse (t) is multiplied by the cycleway factor function.

$$C_{cycleway} = f_{cycleway}(x) * t \tag{3.5}$$

3.6.3 Security

In bicycle routing algorithms, evaluating the safety and security of cyclists in different route segments is an important factor in generating the optimal route. The function $f_{security}(x)$ is designed in order to quantify and penalize the different security levels of various paths and roads that cyclists might encounter. Quantifying the security of the roads and paths is essential and influences the cyclist's route choice, especially when cyclists are in urban environments where traffic conditions might impact their security. Although collisions with motor vehicles are relatively uncommon, they are responsible for most serious injuries and fatalities. [30, 31]

The security factor function $f_{security}(x)$ assigns a penalization to different road segments based on its classification. This weight reflects the relative safety and comfort through that particular segment that a cyclist might experience, the lower the penalization value, the safer and more suitable the road segment is for cyclists.

$$f_{security}(x) = \begin{cases} 0.4 & \text{if } x \text{ is a cycleway,} \\ 0.8 & \text{if } x \text{ is pedestrian or footway,} \\ 1.5 & \text{if } x \text{ is a secondary or secondary\_link,} \\ 1.5 & \text{if } x \text{ is a trunk or trunk\_link,} \\ 2 & \text{if } x \text{ is a primary or primary\_link,} \\ 1 & \text{otherwise} \end{cases} \tag{3.6}$$

Delving into the penalization of the different road segments:

- **Cycleways:** These paths are specifically designed for cyclists, offering the highest safety with minimal interaction with motorized vehicles. Consequently, it is assigned the lowest security factor at 0.4, which indicates the safest and most desirable option for cyclists.

- **Pedestrian or Footways:** These paths are shared with pedestrians while still providing a safer environment due to the absence of motorized vehicles, the presence of pedestrians creates potential conflicts and slower travel time, offering a less suitable alternative to cycleways but still good hence the 0.8 security factor.

- **Secondary and Trunk Roads (including their links):** These roads have more vehicle traffic and often higher speeds and volumes of cars, which can become intimidating and less safe for cyclists. Therefore, they are assigned a security factor of 1.5, reflecting the potential higher risk associated with cycling.

- **Primary Roads and Links:** These main roads typically have heavy traffic traveling at higher speeds. This interaction is the unsafest for cyclists, resulting in the highest security factor of 2, signaling the algorithm to avoid these roads if possible, especially when safer alternatives are available.

- **Other Roads:** Other road classifications are considered to be balanced between safety and speed. Therefore, no penalization, positive or negative, is associated with these roads.

The function $f_{security}(x)$ represents a crucial element of the bicycle routing algorithm, with a trade-off between safety and speed, integrating the perceived safety of the various pathways into the route planning process, ensuring that every route is not only efficient but also secure.

$$C_{security} = f_{security}(x) * t \tag{3.7}$$

3.6.4 Slope

The topographical features of a route, especially the slope, are extremely important for cyclists as they determine the difficulty and feasibility of a path. With this into account, the function $f_{slope}(x)$

is designed to assess and integrate these topographical challenges into the routing algorithm, ensuring that cyclists receive feasible routes.

$$f_{slope}(slope,length) = \begin{cases} 1.2 & 2 < slope < 4 \quad \wedge \quad length > 4000, \\ 1.2 & 4 < slope < 5 \quad \wedge \quad length > 2000, \\ 1.2 & 5 < slope < 6 \quad \wedge \quad length > 240, \\ 1.2 & 6 < slope < 7 \quad \wedge \quad length > 120, \\ 1.2 & 7 < slope < 8 \quad \wedge \quad length > 90, \\ 1.2 & 8 < slope < 9 \quad \wedge \quad length > 60, \\ 1.2 & 9 < slope < 10 \quad \wedge \quad length > 30, \\ 1.2 & slope > 10 \quad \wedge \quad length > 15, \\ 0.8 & slope < 0, \\ 1 & \text{otherwise} \end{cases} \tag{3.8}$$

The values presented for slope and length in this function are present in table 2.5. Moreover, any of the values that are considered to be feasible from [16] have a slope factor of 1, the paths that have a negative slope value which represents a downhill, a factor of 0.8 is assigned in order to preferably choose paths that are downhill and paths that the length surpasses the max recommended for a determine slope value of the path are given a factor of 1.2.

$$C_{slope} = f_{slope}(slope,length) * t \tag{3.9}$$

3.6.5 Effort

In the context of bicycle routing, the effort required to traverse different road segments is a significant factor. It impacts the physical exertion cyclists need to invest, particularly on slopes, it quantifies this exertion, integrating it into the overall routing algorithm to ensure the generated paths are not only efficient but also within the cyclist's physical capabilities.

The function $f_{effort}(s,l)$ is designed to account for the effort required based on the slope (s) and the length (l) of the road segment. Different slopes and lengths result in varying levels of effort, which this function aims to capture accurately.[32]

$$f_{effort}(s,l) = \begin{cases} 1.5 & \text{slope} < -30, \\ 1 + 2\frac{0.7}{13} \cdot \text{slope} + \frac{0.7}{13^2} \cdot \text{slope}^2 & -30 \le \text{slope} < 0, \\ 1 + \left(\frac{\text{slope}}{g(\text{slope,length})}\right)^2 & 0 < \text{slope} \le 20, \\ 10 & 20 < \text{slope} \end{cases} \tag{3.10}$$

This function considers both positive and negative slopes, applying different formulations based on the slope's range to accurately represent the varying degrees of effort required for different inclines and declines.[32]

$$g(slope, length) = \begin{cases} 4 & 10 < \text{slope} \leq 13 \quad \wedge \quad \text{length} > 15, \\ 4.5 & 8 < \text{slope} \leq 10 \quad \wedge \quad \text{length} > 30, \\ 5 & 5 < \text{slope} \leq 8 \quad \wedge \quad \text{length} > 60, \\ 6 & 3 < \text{slope} \leq 5 \quad \wedge \quad \text{length} > 120, \\ 7 & \text{otherwise} \end{cases} \tag{3.11}$$

This function $g(slope, length)$ adjusts the perceived effort for uphill segments based on specific slope and length thresholds. It assigns lower values to segments with higher slopes or longer lengths, reflecting the increased effort required for such conditions.

$$C_{effort} = f_{effort}(s, l) * t \tag{3.12}$$

This cost function integrates the effort into the overall route cost, ensuring that routes requiring significant physical exertion are appropriately penalized, thus guiding the algorithm to prefer more manageable paths for the cyclist.

3.6.6 Pavement type

The function $f_{surface}(x)$ calculates a factor based on the type of pavement, which influences the overall traversal cost. This factor helps in determining the efficiency and comfort of different surfaces for various road segments.

$$f_{surface}(x) = \begin{cases} 0.8 & \text{if } surface \text{ is a asphalt, paved or concrete,} \\ 0.9 & \text{if } surface \text{ is wood or compacted,} \\ 1.2 & \text{if } surface \text{ is paving\_stones, sett, pebblestone or cobblestone,} \\ 1.5 & \text{if } surface \text{ is unpaved, fine\_gravel or gravel,} \\ 2 & \text{if } surface \text{ is dirt, earth or earth,} \\ 1 & \text{if } surface \text{ is null} \end{cases} \tag{3.13}$$

The surface factor function assigns specific values to different pavement types to reflect their impact on traversal. For instance, smoother surfaces like asphalt, paved, and concrete are given a lower factor of 0.8, indicating higher efficiency and comfort. Rougher surfaces like dirt and earth are assigned a higher factor of 2, reflecting increased difficulty and less comfort while riding.

Moreover, 2/3 of the whole road network does not specify its surface type, and in order to not penalize the roads where information is not given, because although secondary roads are mainly asphalt, there could be some that have other surface types, and we cannot assume its type, so for cases where the surface type is not specified (null), a default factor of 1 is used.

The cost function for the surface factor is presented in the equation below, where the traversal cost (t) is multiplied by the surface factor function.

$$C_{surface} = f_{surface}(surface) * t \tag{3.14}$$

3.6.7 Total Cost

The multiple factors affecting a cyclist's journey must be integrated to produce a cost function that accurately reflects the real-world preferences and challenges faced by cyclists. The total cost function aggregates these individual costs to guide the algorithm in choosing the most optimal route.

3.6.7.1 Formulating the Total Cost Function

The total cost function C_{total} is defined as a weighted sum of the individual cost functions for each factor. This allows the algorithm to consider the relative importance of each factor in the routing decision. The general form of the total cost function is:

$$C_{total} = w_{speed} * C_{speed} + w_{cycleway} * C_{cycleway} + w_{security} * C_{security} + w_{slope} * C_{slope} + w_{effort} * C_{effort} + w_{surface} * C_{surface} \tag{3.15}$$

Where:

- w_{speed}, $w_{cycleway}$, $w_{security}$, w_{slope}, w_{effort} and $w_{surface}$ are the weights assigned to each factor.
- C_{speed}, $C_{cycleway}$, $C_{security}$, C_{slope}, C_{effort} and $C_{surface}$ are the individual cost functions for speed, cycleway presence, security, slope, effort, and surface type, respectively.

Each weight reflects the relative importance of the corresponding factor, allowing the routing algorithm to emphasize or de-emphasize specific aspects of the route according to the cyclist's preferences.

3.7 Summary

The solution for routing optimization detailed in this chapter outlines the comprehensive processes undertaken to optimize routes for bicycle users in the district of Porto. From data acquisition and integration to the incorporation and creation of road network topology and elevation data, each step was meticulously executed to ensure quality, accuracy, and practical route recommendations. The use of PostgreSQL with PostGIS for spatial data storage and QGIS for visualization facilitated the management and analysis of geospatial data. Elevation data from NASA's SRTM was integrated to calculate the slopes of road segments, essential for determining the effort and difficulty of the route. This chapter also covers the application of Dijkstra's algorithm to develop a directed road network that considers various factors, such as slope, safety, and surface type, to generate optimal bicycle routes.

Chapter 4

Evaluation

In this chapter, we will delve into the results of the research survey, this survey was made for people who regularly use bicycles as their mode of transportation, whether for leisure, sport, or going to work, and the primary objective of this survey is to understand the factors that influence cyclists' route choices and to use this information to optimize the route planning algorithm for bicycle users in the city of Porto, and 21 cyclists participated in this research.

4.0.1 General characteristics of the participants

Participants in this study ranged in age from 18 to 75 years. The majority of participants were between 30 and 60 years old, representing 62% of the sample.

Table 4.1: General characteristics of survey participants

Age (years)		Electric Bicycle	
		Yes	No
18 to 30	14,29%	33.3%	66.6%
30 to 45	23,81%	40%	60%
45 to 60	38,10%	62.5%	37.5%
> 60	23,81%	80%	20%

We can also observe that Participants over 60 years old also show a high ownership rate of electric bicycles at 80%, indicating a strong preference for electric bicycles in older age groups, and younger participants (18 to 30 years) have a lower ownership rate of electric bicycles (33.3%), this tendency grows as people age, although nowadays it is increasingly normal for people who use a bicycle on a daily basis to have an electric bicycle, it is becoming one of the main factors why people use the bicycle regularly.

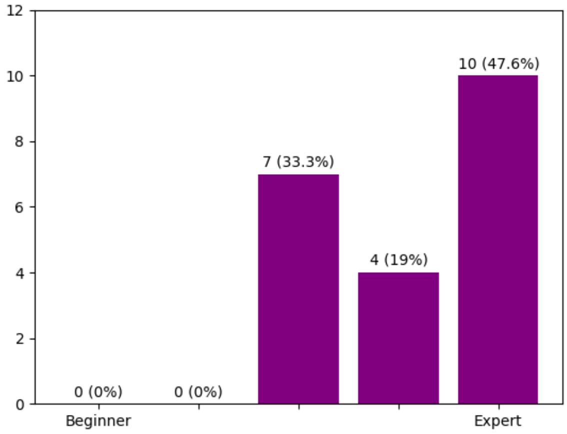


Figure 4.1: Cyclist Expertise Level Distribution

The bar chart presented illustrates the distribution of cyclist expertise levels among the survey participants showing a clear trend where a significant number of participants have advanced or expert-level cycling skills. These higher expertise levels could influence the preferences and feedback gathered in the surveys, as more experienced cyclists might prioritize different route characteristics compared to beginners.

The bar chart 4.2 illustrates the various purposes for which survey participants use their bicycles and the frequency with which they do so. The data is categorized into four main purposes: Utilitarian Transport, Commute to Work/Study, Sports, and Leisure (Trips). For each purpose, the frequency of use is further divided into five categories: Never, a few times a year, a few times a month, several times a week, and Daily.

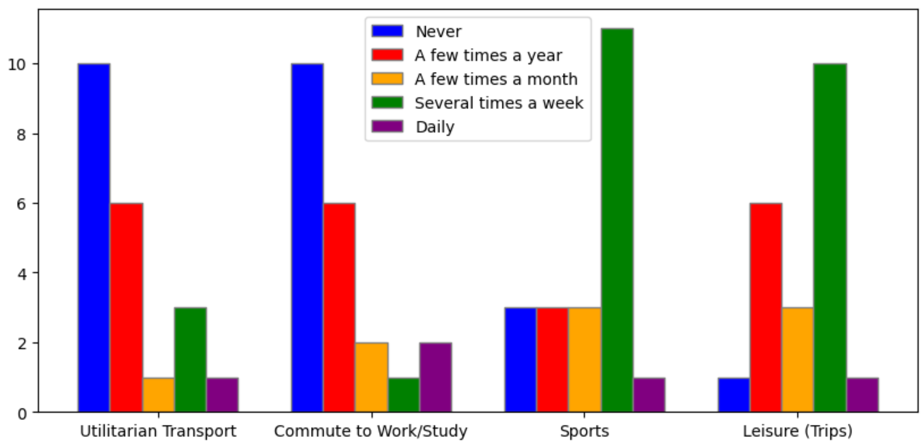


Figure 4.2: Purpose of Bicycle Use and Frequency

As we can observe, a high number of participants never use their bicycles as a way to get to work or to go, for example, to the supermarket, this reveals that in the city of Porto, there might be barriers such as a lack of bicycle infrastructure, safety concerns or simply inconvenience. Sports and leisure activities are the main purpose why participants use their bicycles, revealing that participants view cycling as a recreational activity rather than a primary mode of transportation.

4.0.2 Importance of factors

In figure 4.3, we observe the importance ratings assigned by participants to the different factors that influence their choice when planning a route, the closer to 5, the more importance the factor has. The graph clearly shows that "Safety in circulation" is considered the most important factor, with an average rating of (4.57), closely followed by "Vehicle circulation speed" with (4.43) and "Heavy traffic areas" with (4.24). These findings underscore the critical importance of safety and traffic conditions in cyclists' route preferences, other factors such as the "Effort level" (3.24), the "Existence of cycleway" (3.10), and "Inclination of roads" (3.05) also play significant roles, and on the lower end of the spectrum, are factors like "Familiarity with the route" (2.47) and "Speed" (2.76) which are deemed less critical compared to the others.

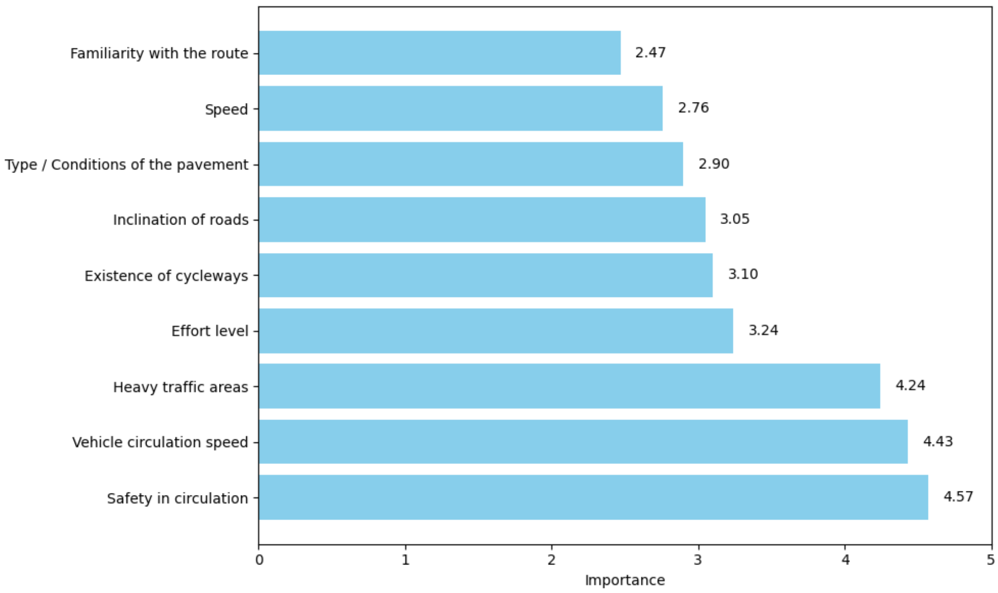


Figure 4.3: Importance of the factors when choosing a route

Moreover, as shown in figure 4.4, participants revealed distinct preferences regarding which factor they deemed the most important.

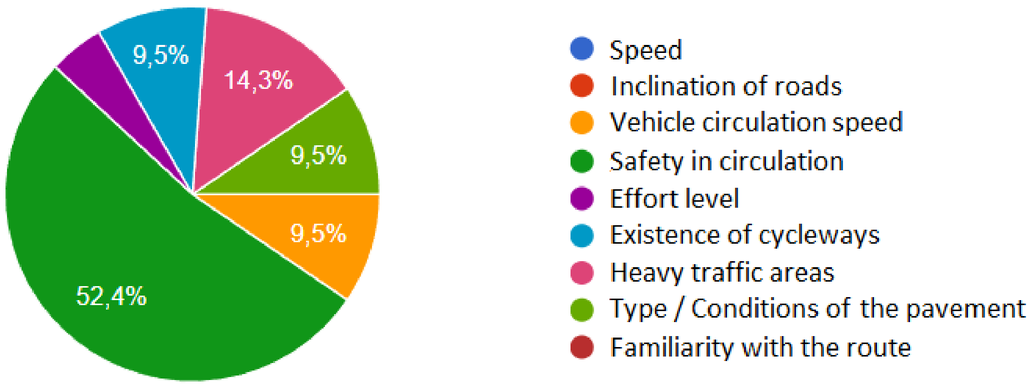


Figure 4.4: Most important factor users considered to be when making a route

In regards to safety, we could say that 52.4% of the participants assigned safety as the most important factor when selecting a route.

Given the insights from the survey and taking a look at the total cost function 3.6.7.1, we can establish a general order of importance for the factors present in the function in order to refine it and ensure that the most critical factors are given a higher weight in the route planning process:

- Security > Effort > Cycleways > Surface > Slope > Speed.

These findings will directly influence the development of the routing algorithm, ensuring that it prioritizes these critical factors. By incorporating real-world cyclist preferences into the model, the resulting routes will be safer, more comfortable, and more aligned with the needs of the cycling community.

4.1 Different profiles

When planning routes and using the data gathered, cyclists were divided into three distinct profiles: commuters, sports enthusiasts, and leisure riders. Each profile has unique preferences and requirements that influence their route choices.

4.1.1 Commuters

Commuters are riders who use their bicycles primarily for utilitarian purposes such as traveling to work, going to the supermarket, or going to school.

4.1.1.1 Key characteristics

- **Safety:** High priority on routes with dedicated bike paths and with minimal interaction with vehicular traffic.
- **Efficiency:** Commuters prefer direct and time-efficient routes, avoiding big or unnecessary detours.

4.1.1.2 General weight profile

The table in Figure 4.5 and the resulting weights in table 4.2, derived from pairwise comparisons, provide a comprehensive understanding of the preferences of commuter cyclists, whose primary focus is on efficient, safe, and smooth routes for their daily travels.

Table 4.2: Resulting weights for the criteria on pairwise comparisons Commuter Profile

Criteria	**Priority/Weight**	**Rank**
Effort	18.7 %	4
Security	20.2 %	3
Speed	30.4 %	1
Slope	4.1 %	6
Cycleway	6.0 %	5
Surface	20.7 %	2

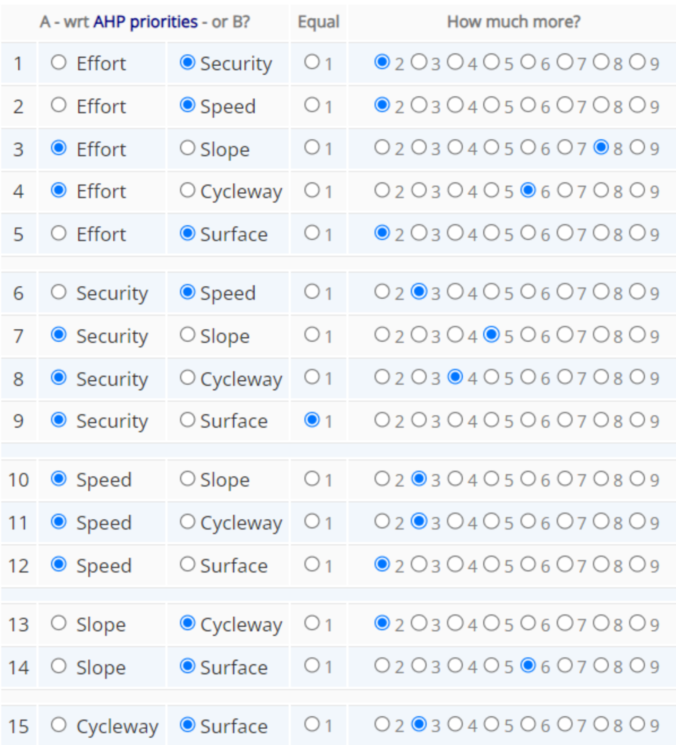


Figure 4.5: AHP pairwise comparison for the commuter profile

Figure 4.5 shows a pairwise comparison table where each criterion is rated from 1 to 9 in respect to the others.

Analyzing the table 4.2 we can observe that speed (30.4%) is the top priority for commuter cyclists, highlighting the need for direct routes that minimize travel time, surface quality (20.7%) is also crucial, indicating a preference for smooth roads which provide more comfort and enables higher speeds when riding, as well as safety (20.2%) which is equally important, planning routes that minimize car traffic exposure. While some elevation changes are tolerated (effort: 18.7%), excessively hilly routes are less desirable. Interestingly, dedicated cycleway presence does not have that much importance (6.0%), suggesting other factors like safety and directness take precedence for commuters. Finally, the slope criteria has the least influence (4.1%), implying a focus on efficiency and safety over unnecessary detours. These insights are crucial for designing cycling routes that effectively cater to commuter needs for daily travel.

4.1.2 Sports enthusiasts

Sports enthusiasts use their bicycles as a way to stay active and do physical exercise, valuing routes that provide smoothness and are not bothered with routes that have a higher level of effort.

4.1.2.1 Key characteristics

- **Quality of Infrastructure:** Sports enthusiasts prefer high-quality cycle paths that are smooth to ride and free of obstructions.

- **Effort:** Sports enthusiasts do not mind if a route has a high level of effort.

4.1.2.2 General weight profile

Sports enthusiasts prioritize riding safely and performing at a high level. Their preferences are well-understood by looking at the table in Figure 4.6 and the weights that follow from the pairwise comparisons in Table 4.3, using information gathered from surveys and research to conduct these pairwise comparisons, guaranteeing that the resulting priorities fairly reflect the preferences of this group.

The pairwise comparison table, figure 4.6, rates each criterion's relative value from 1 to 9 in relation to the others.

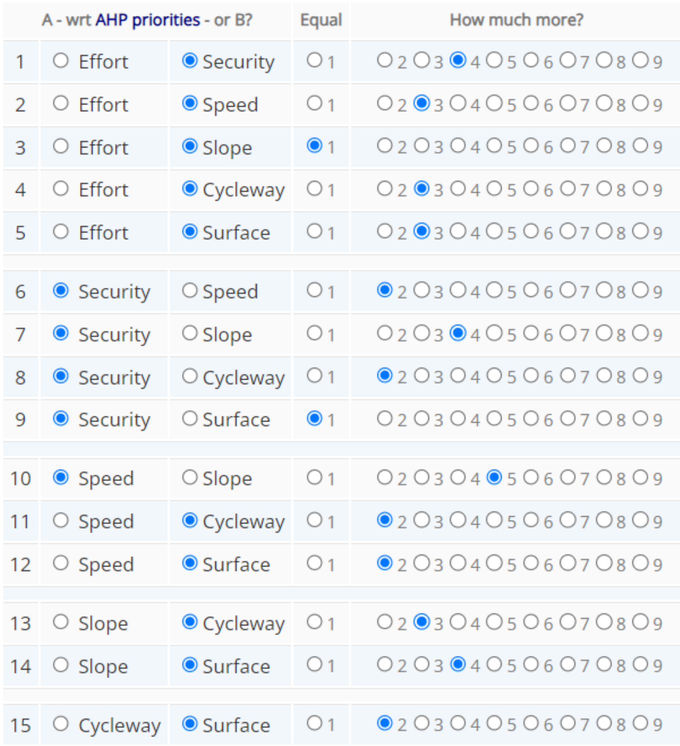


Figure 4.6: AHP pairwise comparison for the sports profile

Based on these pairwise comparisons, the resulting priorities for sports enthusiasts are presented in table 4.3.

Table 4.3: Resulting weights for the criteria on pairwise comparisons Sports Profile

Criteria	**Priority/Weight**	**Rank**
Effort	6.3 %	5
Security	27.5 %	1
Speed	16.0 %	4
Slope	5.6 %	6
Cycleway	18.2 %	3
Surface	26.4 %	2

The pairwise comparisons were conducted using data gathered from surveys and research, ensuring that the resulting priorities accurately reflect the preferences of this group. The analysis reveals that security is the top priority for sports enthusiasts, with a weight of 27.5%, emphasizing the need for safe routes with minimal traffic interaction, also surface quality follows closely at 26.4%, indicating a preference for smooth, well-maintained roads that support optimal cycling performance, the presence of dedicated cycleways is also significant, with a weight of 18.2%, reflecting the value placed on infrastructure which provides a safe environment for rider to exercise, and speed is also important as well, with a weight of 16.0%, highlighting the need for routes that allow a higher speed when cycling. Effort (6.3%) and slope (5.6%) are less critical because challenging terrain and physical exertion are accepted. These insights can guide the development of cycling routes that cater specifically to sports enthusiasts, ensuring their route is more focused on their safety and comfort while enabling a higher speed along the route.

4.1.3 Leisure riders

Leisure riders use their bicycles for recreational purposes, such as casual rides, exploring new areas, or family outings. This group enjoys the experience of cycling and values comfort and pleasant surroundings.

4.1.3.1 Key characteristics of Leisure Riders

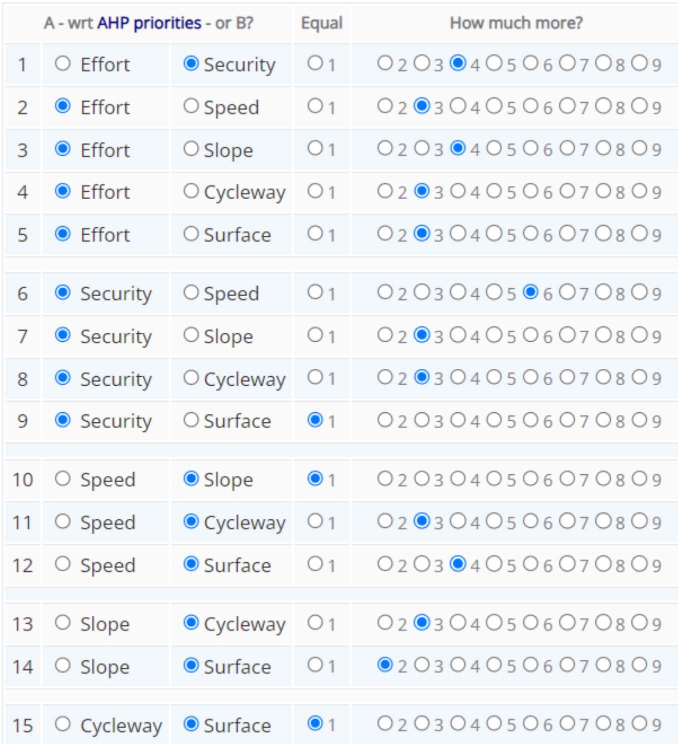
- **Comfort:** Leisure riders prefer smooth, flat paths that are easy to navigate, making the ride enjoyable and stress-free.

- **Security:** Leisure riders prioritize routes with dedicated bike paths and with minimal interaction with vehicular traffic.

4.1.3.2 AHP Analysis for Leisure Riders

The table in figure 4.7 and resulting weights on table 4.4 derived from the pairwise comparisons provide a detailed insight into the preferences of leisure riders, whose primary concern is to enjoy a comfortable, scenic, and safe cycling experience. The pairwise comparisons were conducted using data gathered from surveys and research, ensuring that the resulting priorities accurately reflect the preferences of this group.

The table of pairwise comparisons, figure 4.7, shows the relative importance of each criterion when evaluated against others, rated on a scale from 1 to 9.



	A - wrt AHP priorities - or B?		Equal	How much more?
1	Effort	**Security**	1	**4**
2	**Effort**	Speed	1	**3**
3	**Effort**	Slope	1	**4**
4	**Effort**	Cycleway	1	**3**
5	**Effort**	Surface	1	**3**
6	**Security**	Speed	1	**6**
7	**Security**	Slope	1	**3**
8	**Security**	Cycleway	1	**3**
9	**Security**	Surface	**1**	
10	Speed	**Slope**	**1**	
11	Speed	**Cycleway**	1	**3**
12	Speed	**Surface**	1	**4**
13	Slope	**Cycleway**	1	**3**
14	Slope	**Surface**	1	**2**
15	Cycleway	**Surface**	**1**	

Figure 4.7: AHP pairwise comparison for the leisure profile

Based on these pairwise comparisons, the resulting priorities for leisure riders are presented in table 4.4.

Table 4.4: Resulting weights for the criteria on pairwise comparisons Leisure Profile

Criteria	**Priority/Weight**	**Rank**
Effort	24.2 %	2
Security	35.8%	1
Speed	5.1 %	6
Slope	6.3 %	5
Cycleway	12.6 %	4
Surface	16.0 %	3

Observing table 4.4, security emerges as the most important factor with a weight of 35.8%, highlighting the need for safe routes with minimal traffic interaction, effort follows at 24.2%, indicating a preference for easy-to-navigate paths that do not require significant physical exertion, then surface quality ranks third at 16.0%, emphasizing the importance of smooth, well-maintained paths, Cycleway presence is also significant at 12.6%, reflecting the desire for dedicated cycling infrastructure. Slope and Speed are less critical, with weights of 6.3% and 5.1%, respectively, showing that while gentle slopes are preferred for comfort, speed is the least concern for leisure riders. These priorities underscore the emphasis on safety, comfort, and enjoyment in leisure cycling route planning.

4.1.4 Showcase of the 3 routing profiles: Quinta do Covelo -> Praia dos Ingleses

Figure 4.8 showcases three distinct cycling routes from Quinta do Covelo to Praia dos Ingleses, each tailored to different cyclist profiles: Sports, Leisure, and Commuter.

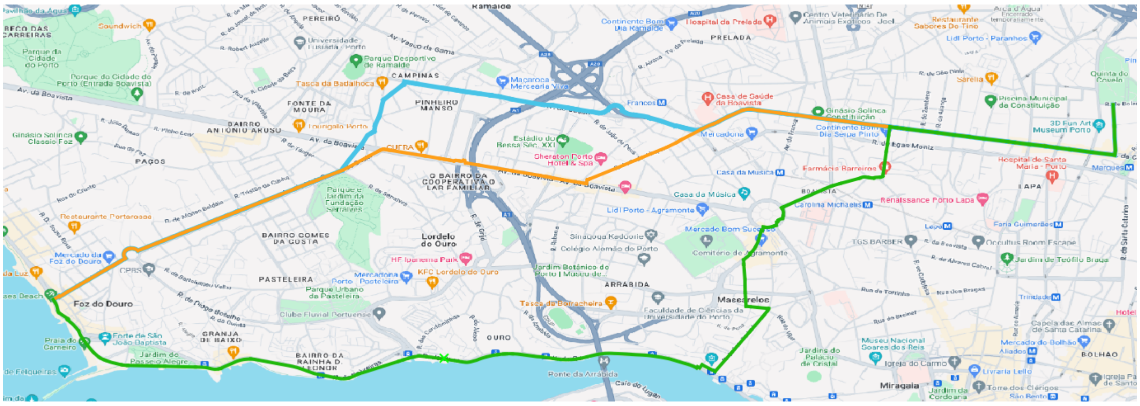


Figure 4.8: The 3 different routing profiles from Quinta do Covelo to Praia dos Ingleses

The sports route, marked in blue, is designed for cyclists looking to do some physical exercise. This route is typically more direct than the leisure route, although it may include more varied terrain, while still maintaining the safety of the cyclist and navigating through less busy streets. This route has smoother paths, allowing for continuous cycling at higher speeds, catering to the needs of sports enthusiasts.

The commuter route, marked in yellow, is designed for efficiency, focusing on the shortest and fastest path to the destination. It emphasizes directness and safety, and avoiding steep inclines where possible. This route takes a relatively direct path through the city, aimed at minimizing travel time while maintaining comfort. The commuter route is optimized for daily use by individuals who need to get from point A to point B quickly and safely, avoiding unnecessary detours.

The leisure route, marked in green, caters to casual and recreational cyclists who prioritize comfort and safety. This route includes dedicated cycle paths where possible, ensuring a safe and enjoyable experience along the coastline and providing a more relaxed ride. The leisure route is longer and more winding, appealing to safety and comfort, offering cyclists a relaxed pace with opportunities to stop and enjoy the surroundings.

The table below provides detailed information about the three different cycling routes present on figure 4.8, tailored to the commuter, sports, and leisure profiles. Each route is characterized by expected travel time, distance, and the types of roads utilized.

Table 4.5: Details of each profile route

Profile	Expected Time	Distance	Road Types			
			Primary	Secondary	Cycleway	Other
Commuter	25 min	7,35 km	16%	56%	16%	12%
Sports	33 min	7,68 km	0%	63%	16%	21%
Leisure	37 min	8,56 km	0%	22%	62%	16%

Observing table 4.5, the commuter route, covering 7.35 km in 25 minutes, prioritizes efficiency and safety with a balanced mix between secondary roads (56%), primary roads (16%), cycleways (16%), and other roads (12%), getting the cyclist from point A to point B the quickest. The sports route, spanning 7.68 km in 33 minutes, has more safety than the commuter route, by avoiding primary roads, and balancing the use of secondary roads (63%), some cycleways (16%), and other roads (21%). The leisure route, at 8.56 km in 37 minutes, focuses on a comfortable experience, extensively using cycleways (62%) and incorporating some secondary roads (22%) and other roads (16%), entirely avoiding primary roads. Each route is meticulously crafted to meet the specific needs of different cyclist profiles, enhancing the cycling experience for commuters, sports enthusiasts, and leisure riders.

Comparing these routes, the commuter route is the most direct, emphasizing efficiency and practicality. The sports route also follows a direct path but includes more challenging segments since cyclists do not mind the effort and prioritize safety. The leisure route, on the other hand, is the longest and most winding, designed to offer a pleasant and comfortable riding experience.

4.2 Summary

The evaluation of the proposed routing optimization approach detailed in this chapter involves a thorough analysis of its effectiveness. The chapter begins by surveying participants to understand their cycling habits and preferences, categorizing them into different profiles such as commuters, sports enthusiasts, and leisure riders. The use of the Analytic Hierarchy Process (AHP) provides valuable insights into the varying preferences and priorities of these different cyclist profiles, highlighting the importance of factors such as safety, comfort, and efficiency in route selection. By employing AHP, the proposed routing algorithm is able to address these prioritized factors, resulting in routes that are better tailored to the unique needs of each profile. This comprehensive methodology lays a robust foundation for the subsequent chapter, where the practical application and the effectiveness of the proposed routing solutions will be further explored and validated.

Chapter 5

Analysis and Discussion of Results

In this chapter, we evaluate the effectiveness and efficiency of the proposed route optimization algorithms by comparing the generated routes with those provided by popular cycling route planning applications such as Google Maps and Komoot and with feedback from a focus group tailored to the routes they usually use. This comparison aims to highlight the unique strengths and potential weaknesses of our approach in terms of the various factors, and with the results, we can determine the practical benefits and areas for improvement in our routing approach. The insights gained from this comparative analysis will provide a comprehensive understanding of the real-world applicability and performance of our proposed methodology.

5.1 Route evaluation

In this section, we present detailed descriptions and visual comparisons of the specific routes used for evaluating the proposed algorithm against other popular cycling route planning applications. Also, through the first survey a focus group was gathered in order to evaluate routes.

Moreover, to facilitate a clear and thorough comparison, we include maps and visual representations of the routes generated by the different routing applications. These visuals help to illustrate the paths taken by each routing solution, highlighting differences and similarities in each route selection.

The Google Maps routes considered were the first options suggested by the application. The routes on Komoot were tailored accordingly to the chosen cyclist profile for each case study.

Every case study was created through routes that were evaluated by people from the focus group who have ridden that specific route various times and know what are the best and worst routes to use.

In the case studies presented, all expected time data was sourced from the same application to avoid discrepancies. This consistent approach ensures that the comparisons between different routes and profiles are fair and reliable, providing a clear understanding of the performance and suitability of each route.

5.1.1 Case study 1: Maia to FEUP

Our approach to this route was planned using the preferences of an individual from our focus group who fits within the leisure profile. Leisure cyclists prioritize comfort and safety over speed.

Figure 5.1: Route given by our approach case study 1.

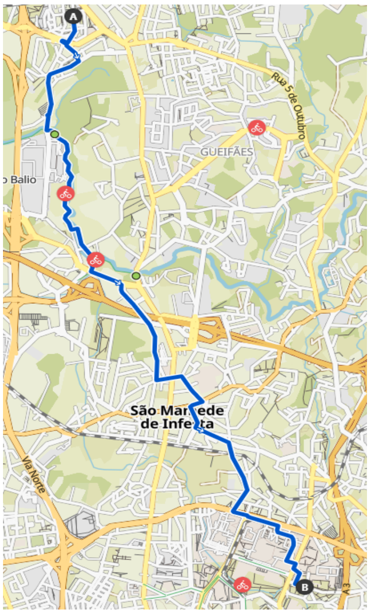


Figure 5.2: Route given by Komoot case study 1.

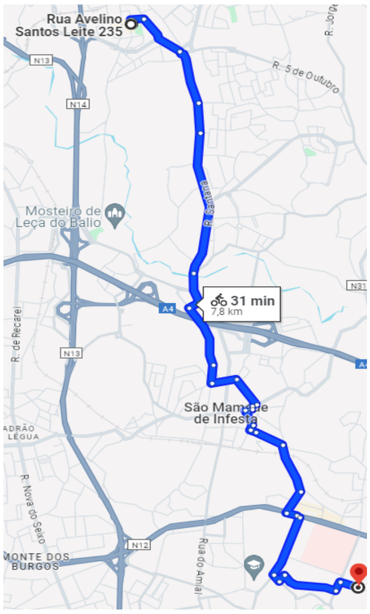


Figure 5.3: Route given by Google Maps case study 1.

Table 5.1: Details of each route for case study 1

Route	Expected Time	Distance	Road Types					
			Primary	Secondary	Cycleway	Streets	Paths	Other
Our approach	45 min	8,16 km	2%	46%	21%	23%	8%	0%
Komoot	42 min	7,77 km	3%	40%	21%	33%	1%	2%
Google Maps	32 min	7.59 km	3%	82%	0%	7%	8%	16%

5.1.1.1 Description of the different routes for case study 1

Our Approach: The route generated by our approach spans a distance of 8.16 km with an expected travel time of 45 minutes. This route prioritizes the use of cycleways to enhance safety and comfort, making it ideal for leisure cyclists.

Komoot: Komoot provides a route that is 7.77 km long, with an estimated travel time of 42 minutes. This route also prioritizes safety and comfort over speed.

Google Maps: The Google Maps route is the shortest and fastest, covering 7.59 km in 32 minutes. This route focuses more on speed, avoiding detours that make the route safer, which does not align well with the leisure profile's preference for safety and comfort.

5.1.1.2 Analysis and User Feedback for case study 1

The feedback demonstrates a high level of satisfaction with the route generated by our approach, particularly in terms of safety, efficiency, and overall alignment with personal preferences. The positive comparison with regular routes and the willingness to use the route regularly in the future further validate the effectiveness of our route planning methodology for leisure cyclists.

For this case study, our approach excels in providing a safe and comfortable route for leisure cyclists by doing some detours to prioritize safety over speed, Komoot also offers a similar balance, but Google Maps, while the fastest and shortest, compromises safety and comfort by focusing on speed and disregarding the use of dedicated cycling infrastructure which does not align with the leisure profile.

This positive feedback validates the effectiveness of our route planning methodology while also recognizing Komoot's strengths in offering a comparable balance between safety and comfort.

5.1.2 Case Study 2: Rua Diogo Cão to Parque Urbano Rio Tinto

Our approach to this route was planned using the preferences of an individual from our focus group who fits within the commuter profile, meaning that speed, surface, and safety are the most important factors.

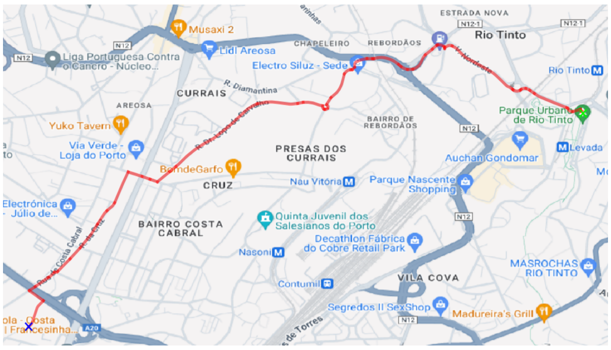


Figure 5.4: Route given by our approach case study 2.

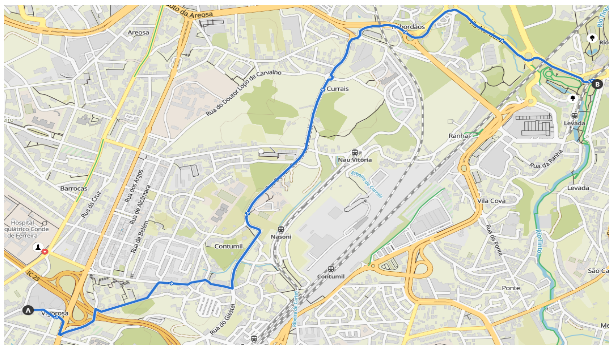


Figure 5.5: Route given by Komoot case study 2.

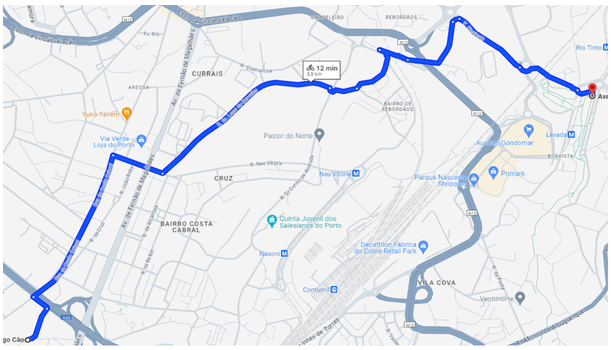


Figure 5.6: Route given by Google Maps case study 2.

Table 5.2: Details of each route for case study 2

Route	Expected Time	Distance	Road Types					
			Primary	Secondary	Cycleway	Streets	Paths	Other
Our approach	14 min	3,70 km	1%	47%	1%	49%	2%	0%
Komoot	12 min	3.92 km	3%	70%	1%	26%	0%	0%
Google Maps	16 min	3.77 km	0%	25%	1%	69%	5%	0%

5.1.2.1 Description of the different routes for case study 2

Our Approach: The route generated by our approach covers a distance of 3.70 km with an expected travel time of 15 minutes.

Komoot: The Komoot route spans 3.92 km and has an estimated travel time of 12 minutes. This route heavily relies on secondary roads, providing a direct and efficient path for commuters.

Google Maps: The Google Maps route is 3.77 km long with an expected travel time of 16 minutes. It uses a higher percentage of streets and paths, potentially compromising speed and surface quality.

5.1.2.2 Analysis and User Feedback for case study 2

The feedback indicates that while the users preferred the Komoot route overall, they also appreciated the route generated by our approach. The Komoot route received higher ratings overall, but our route was still well-regarded.

For this case study, our approach focuses on balancing speed, surface quality, and safety by utilizing secondary roads and streets. The user found this balance satisfactory and indicated a liking for our route due to its careful consideration of these factors. However, the Komoot route excelled by providing a slightly faster and more efficient path through a higher reliance on secondary roads, which the user favored for their better surface quality and directness.

On the other hand, the Google Maps route compromised on surface quality and speed by using a higher percentage of streets and paths, which does not align well with the commuter profile's emphasis on these factors.

Overall, the user feedback for Case Study 2 highlights that while our approach is effective in providing a safe and balanced route, the Komoot route was slightly more aligned with the user's preferences for speed and efficiency, which indicates that while our methodology is on the right track, there may be areas for refinement to better meet the needs and preferences of commuter cyclists.

5.1.3 Case Study 3: Leça do Balio to Moreira

Our approach to this route was planned using the preferences of an individual from our focus group who fits within the sports profile, meaning that surface quality and safety are the most important factors.

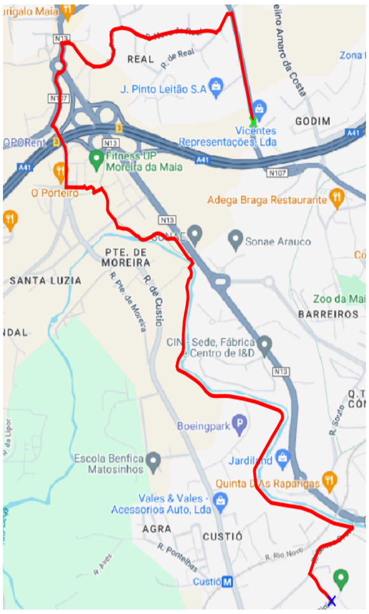


Figure 5.7: Route given by our approach case study 3.

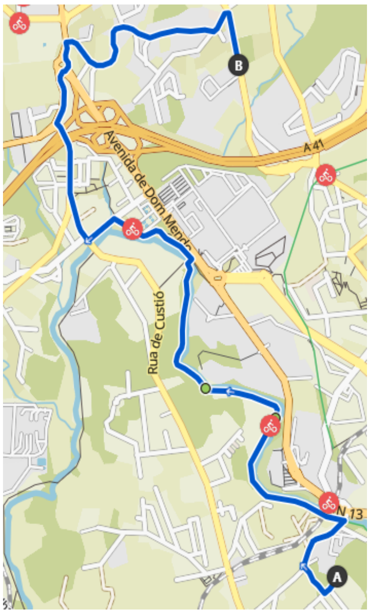


Figure 5.8: Route given by Komoot case study 3.

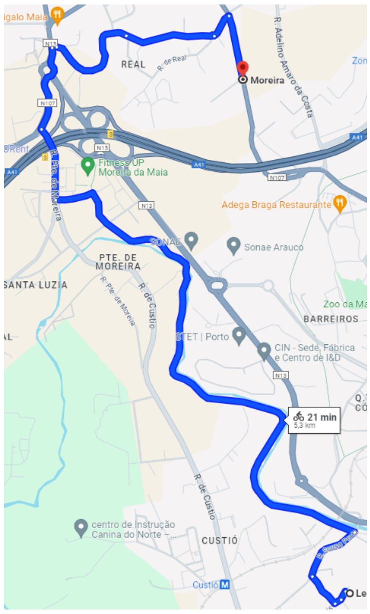


Figure 5.9: Route given by Google Maps case study 3.

Table 5.3: Details of each route for case study 3

Route	**Expected Time**	**Distance**	**Road Types**					
			Primary	Secondary	Cycleway	Streets	Paths	Other
Our approach	29 min	5.34 km	8%	12%	45%	30%	5%	0%
Komoot	33 min	5.56 km	7%	20%	46%	27%	0%	0%
Google Maps	30 min	5.40 km	8%	13%	45%	28%	3%	3%

5.1.3.1 Description of the different routes for case study 3

Our Approach: The route generated by our approach covers a distance of 5.34 km with an expected travel time of 29 minutes.

Komoot: The Komoot route spans 5.56 km with an estimated travel time of 33 minutes.

Google Maps: The Google Maps route is 5.40 km long with an expected travel time of 30 minutes.

Despite slight differences in distance and travel time, the routes generated by our approach, Komoot, and Google Maps are quite similar in terms of their overall characteristics, as we can observe in Figures 5.7, 5.8 and 5.9.

5.1.3.2 Analysis and User Feedback for case study 3

The user feedback for these routes was positive. Despite slight differences in distance and travel time, the overall characteristics of the routes were quite similar. The user appreciated the balance between surface quality and safety across all three routes. The consistency in the proportion of cycleways, which is a significant factor for a user with a sports profile, was particularly noted.

overall, the user's positive reception of all three routes indicates a high level of satisfaction with the routes, underscoring the effectiveness of our approach in meeting the specific needs of users prioritizing surface quality and safety.

5.2 General considerations about our routing approach and model

The objective is to develop a routing approach and a model focused on its ability to address various user needs and preferences, offering a comprehensive solution for cyclists, which seems to have been achieved,

With the objective of our approach in mind, we successfully achieved the capability to create distinct routes for different user profiles. By considering various factors such as gradient, pavement type, and urban obstacles, the algorithm could generate routes that cater specifically to the needs of commuters, sports enthusiasts, and leisure riders, although the model still may require some fine-tuning and calibration in order to work in every part of the district of Porto correctly and accurately, which is very difficult since every route needs to get feedback from a rider, since they are the main evaluators of the routes, outlining the weaknesses and strengths of that route, and how can it be better. Of course, this is not an easy task to do, because gathering several people to evaluate a route in a country where there are not so many people using bicycles as a way of transportation is difficult.

One of the key insights from our research is that not all cyclists can be neatly categorized into predefined profiles, such as commuters, sports enthusiasts, or leisure riders. Many users have unique preferences that do not align perfectly with any single profile. To accommodate this diversity, it might be beneficial to develop an application where users can input their own weights and adjust them according to their specific needs, also enabling the gathering of more information about routes that users prefer ad the weights associated with it. This flexibility would allow for a highly personalized routing experience, ensuring that the route suggestions are tailored to individual preferences, although sometimes users indicate certain preferences but behave differently in real-world scenarios.

The study area chosen for this research was the district of Porto. However, it is important to recognize that the weighting of factors such as safety, comfort, and efficiency may vary significantly in different geographic areas, characteristics and infrastructure of Porto might not be representative of other regions, and thus may require adjustments to reflect the unique conditions and preferences of cyclists in other regions.

Moreover, existing applications often allow users to drag parts of the route to pass through certain points, making it easier to plan or alter the route. This feature enhances user control over route planning, enabling them to create routes that better fit their specific needs and preferences. Implementing similar functionalities in our application could significantly improve user satisfaction and engagement.

All factor values in our routing algorithm are inherently subjective. While we aimed to reach a general consensus on these values, it is essential to recognize that individual perceptions and preferences vary widely. This subjectivity underscores the importance of allowing users to adjust the weights and values according to their personal experiences and needs.

The surveys conducted as part of this research provided valuable insights into user preferences. However, it is important to note that the preferences reported in surveys do not always align with actual behavior or practices. This discrepancy highlights the need for continuous feedback mechanisms and iterative improvements to the routing algorithm based on real-world usage data.

In conclusion, our approach demonstrates the potential and effectiveness of a personalized, multi-criteria routing approach for cyclists. While there are areas for improvement and further development, the findings from this research provide a solid foundation for enhancing the cycling experience and promoting sustainable transportation.

5.3 Summary

This chapter evaluates the effectiveness, efficiency and considerations of the proposed route optimization algorithms by comparing them to popular cycling routes planning applications like Google Maps and Komoot, along with feedback from a focus group. Through detailed analysis of three case studies, the routes were tailored to different cyclist profiles: leisure, commuter, and sports. Visual comparisons and user feedback highlighted the strengths and weaknesses of each approach. Our methodology demonstrated a strong balance between safety, comfort, and efficiency, particularly for leisure and sports cyclists. While Komoot slightly outperformed in speed and efficiency for commuters.

Chapter 6

Conclusions

In this chapter, we summarize the key findings of our research on route optimization for bicycle users, addressing the current limitations, academic developments, and potential directions for future work. This study has explored the multifaceted nature of bicycle routing, integrating various factors to create a more personalized and efficient routing system.

6.1 Key Findings

Our research demonstrates the potential and effectiveness of a personalized, multi-criteria routing approach for cyclists. By considering various factors such as gradient, pavement type, and urban obstacles, the algorithm can generate routes that cater specifically to the needs of commuters, sports enthusiasts, and leisure riders.

One of the key insights from our research is that not all cyclists can be neatly categorized into predefined profiles. Many users have unique preferences that do not align perfectly with any single profile. To accommodate this diversity, it may be beneficial to develop an application where users can input their own weights and adjust them according to their specific needs. This flexibility would allow for a highly personalized routing experience, ensuring that the route suggestions are tailored to individual preferences.

6.2 Current Limitations of the approach

Despite the promising benefits, our approach has several limitations. The complexity of incorporating a wide range of preferences can raise computational challenges. Additionally, gathering and maintaining accurate and comprehensive data on cyclists is an ongoing challenge. The subjective nature of prioritizing and weighting different cyclist preferences might need an overall consensus, which can be difficult to achieve.

The study area chosen for this research was the district of Porto. The characteristics and infrastructure of Porto might not be representative of other regions, requiring adjustments to reflect the unique conditions and preferences of cyclists in other areas.

6.3 Academic Developments

Our approach opens the way for future research in the field of bicycle routing. The findings provide a solid foundation for further exploration and refinement of multi-criteria routing algorithms. Future studies could explore the integration of real-time data and advanced machine-learning techniques to enhance the accuracy and efficiency of the routing algorithms.

Surveys conducted among cyclists in Porto were instrumental in understanding their specific needs and preferences, providing valuable data on factors such as safety, preferred routes, and common obstacles faced by cyclists on a daily basis. Incorporating this empirical data into our routing algorithm significantly improved its relevance and accuracy, making it more attuned to the actual experiences of cyclists.

Moreover, existing applications often allow users to drag parts of the route to pass through certain points, enhancing user control over route planning. Implementing similar functionalities in our application could significantly improve user satisfaction and engagement.

6.4 Future Work

Future work should focus on addressing the current limitations.

First, enhancing data collection methods to gather comprehensive and accurate data on cyclist preferences and behavior should be a priority to develop and make the approach even more realistic, tailoring the various real-world scenarios, while integrating real-time data, such as traffic conditions and air conditions, could further improve the routing recommendations.

Moreover, the development of a continuous feedback mechanism to gather real-world usage data and iteratively improve the routing algorithm with machine-learning techniques to analyze user-designed routes and infer preferences can create more accurate and dynamic user profiles. This could involve creating platforms for users to easily report their experiences and preferences or gather data directly from the application, possibly automating the personalization process. Also, allowing users to input their own weights and preferences, and adjusting the routing algorithms to accommodate these inputs. This could involve developing machine learning models that learn from user feedback and dynamically adjust the routing recommendations based on the specific cyclist profile.

Finally, expanding the area study to include different geographic areas to ensure that the approach can be accurately adapted to various regions could be very important, showcasing the ability for the routing approach to easily be calibrated for different urban infrastructures and cyclist behaviors.

In conclusion, our research highlights the importance of personalized, multi-criteria routing approaches for cyclists. While there are areas for improvement and further development, the findings from this study provide a solid foundation for enhancing the cycling experience and promoting sustainable transportation. The proposed approach holds the potential to contribute to navigation for cyclists by presenting safer, more enjoyable, and accessible cycling experiences for everyone, which may also contribute to sustainable transportation, improved urban planning, and a more engaged cycling community.

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.1 Appendix A - Survey form used to collect data from participants

Optimização de Rotas para Utilizadores de Bicicletas

Este inquérito insere-se no contexto da minha Tese de Mestrado em Engenharia na Faculdade de Engenharia da Universidade do Porto, com o tema "Otimização de Rotas para Utilizadores de Bicicletas". A minha investigação visa compreender melhor as necessidades e preferências dos ciclistas urbanos e optimizar o planeamento de rotas para utilizadores de bicicletas.

Responsável pelo inquérito: João Freitas (up202202489@edu.fe.up.pt)

Orientador e Co-Orientador: António Coelho (acoelho@fe.up.pt) e Rosaldo Rosetti (rossetti@fe.up.pt)

Público-alvo: **pessoas que utilizam bicicleta.**

As respostas recolhidas serão tratadas de forma confidencial e serão utilizadas exclusivamente para fins académicos.

O preenchimento deste formulário é estimado entre 5 a 10 minutos.

Agradeço desde já a sua colaboração e disponibilidade.

* Indica uma pergunta obrigatória

1. **1) Email** *

____

2. **2) Idade**

____

3. **3) Género** *

Marcar apenas uma oval.

( ) Masculino
( ) Feminino

4. **4) Nas suas deslocações diárias habituais, qual o modo de transporte que mais utiliza?** *
Caso utilize mais do que 1 modo predominante, selecione a combinação

Marque todas que se aplicam.

- [ ] Automóvel
- [ ] Motociclo
- [ ] Bicicleta
- [ ] Autocarro
- [ ] Metropolitano
- [ ] Comboio
- [ ] Essencialmente a Pé

5. **5) Com que finalidade utiliza a bicicleta?** *
Selecione a frequência para cada finalidade

Marcar apenas uma oval por linha.

	Nunca	Raramente / algumas vezes por ano	Esporadicamente/ Algumas vezes ao mês	Algumas vezes por semana / Aos fins de semana	No dia-a-dia
Transporte utilitário/ deslocações dentro da cidade (ir ao supermercado, etc))	◯	◯	◯	◯	◯
Deslocação para o trabalho/ estudo	◯	◯	◯	◯	◯
Desporto	◯	◯	◯	◯	◯
Lazer (passeios)	◯	◯	◯	◯	◯

6. **6) Como se considera como utilizador de bicicleta? ***

Marcar apenas uma oval.

	1	2	3	4	5	
Prin	◯	◯	◯	◯	◯	Experiente

7. **7) A bicicleta dispõe de motor elétrico? ***

Marcar apenas uma oval.

◯ Sim

◯ Não

8. **8) Dos seguintes fatores, indique a ponderação que têm na escolha da sua rota?** *
Sendo 0 sem importância e 5 muita importância

Marcar apenas uma oval por linha.

	0	1	2	3	4	5
Rapidez	◯	◯	◯	◯	◯	◯
Inclinação das vias	◯	◯	◯	◯	◯	◯
Velocidade de circulação dos automóveis	◯	◯	◯	◯	◯	◯
Segurança na circulação	◯	◯	◯	◯	◯	◯
Nível de esforço	◯	◯	◯	◯	◯	◯
Existência de ciclovias	◯	◯	◯	◯	◯	◯
Zonas de tráfego automóvel intenso	◯	◯	◯	◯	◯	◯
Tipo de Pavimento	◯	◯	◯	◯	◯	◯
Familiaridade com a rota	◯	◯	◯	◯	◯	◯

9. **9) Dos fatores anteriores qual deles é o que considera ter mais importância?** *

Marcar apenas uma oval.

- Rapidez
- Inclinação das vias
- Velocidade de circulação dos automóveis
- Segurança na circulação
- Nível de esforço
- Existência de ciclovias
- Zonas de tráfego automóvel intenso
- Tipo / Condições do Pavimento
- Familiaridade com a rota

Rotas que utiliza regularmente

Indique 1 ou até 3 rotas que utilize regularmente (pode indicar a rua ou o local)

10. **Rota 1:** Ponto de partida *

11. **Rota 1:** Destino *

12. **Rota 2:** Ponto de partida

13. **Rota 2:** Destino

14. **Rota 3:** Ponto de Partida

15. **Rota 3:** Destino

Optimização de Rotas para Utilizadores de Bicicletas

16. **Gostaria de ser contactado(a) para classificar a(s) sua(s) rota(s) criada(s) com base nas suas preferências?** *

Marcar apenas uma oval.

- Sim
- Não

Este conteúdo não foi criado nem aprovado pelo Google.

Google Formulários

.2 Appendix B - Survey form used to evaluate routes

Avaliação das Suas Rotas

Bem-vindo(a) ao formulário de **Avaliação das suas rotas**!

Este formulário visa recolher a sua opinião sobre as rotas que foram geradas especificamente para si. A sua avaliação é fundamental para compreender se as rotas atendem às suas necessidades e preferências, bem como para identificar áreas de melhoria.

Responsável pelo inquérito: João Freitas (up202202489@edu.fe.up.pt)

Orientadores: António Coelho (acoelho@fe.up.pt) e Rosaldo Rosetti (rossetti@fe.up.pt)

* Indica uma pergunta obrigatória

Rota1: Rua de Diogo Cão -> Rio Tinto

http://youtube.com/watch?v=_dcdr4oRcCg

Avaliação Geral da Rota

1. **1)** Como classificaria de um modo geral a rota fornecida? *

Marcar apenas uma oval.

	1	2	3	4	5	
Muit	◯	◯	◯	◯	◯	Muito Satisfeito

Critérios Específicos de Avaliação

2. **2)** Classifique a segurança da rota em termos de tráfego automóvel e infraestruturas para ciclistas *

Marcar apenas uma oval.

	1	2	3	4	5	
Muit	◯	◯	◯	◯	◯	Muito Seguro

3. **3)** Considera a rota rápida e eficiente para o seu trajeto? *

Marcar apenas uma oval.

	1	2	3	4	5	
Muit	◯	◯	◯	◯	◯	Muito Eficiente

4. **4)** Avalie a familiaridade e a facilidade de navegação nesta rota. *

Marcar apenas uma oval.

	1	2	3	4	5	
Muit	◯	◯	◯	◯	◯	Muito Fácil

5. **5)** Em que medida a rota atendeu às suas preferências pessoais? *

Marcar apenas uma oval.

	1	2	3	4	5	
Nad	◯	◯	◯	◯	◯	Perfeitamente

Avaliação Comparativa

6. **6)** Como compararia esta rota com outras que utiliza regularmente? *

Marcar apenas uma oval.

	1	2	3	4	5	
Muit	◯	◯	◯	◯	◯	Muito Superior

7. **7)** Consideraria usar esta rota regularmente no futuro? *

Marcar apenas uma oval.

- ◯ Sim
- ◯ Não
- ◯ Talvez