CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

Department of Landscape and Urban Planning

Spatial Distribution of Urban Green Infrastructure and Bicycling Activity in Prague: Integrity, Connectivity, and Functionality

Diploma Thesis

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Objectives of thesis

Thesis aims to analyze the interrelationship between infrastructure associated with non-motorized types of transport and urban green spaces of Prague by measuring and quantifying the level of connectivity and integrity between these two systems. The goal is to determine the qualities typical for urban green spaces and bicycling infrastructure in Prague. Analysis will gauge the benefits and intensity of use of the main segments of current cycling routes system. The goal will be for urban planners to use this research to plan for safer riding conditions, enabling wider groups of people to become users of non-motorized modes of transport. The goal of the research will also be to identify the qualitative elements of both systems, allowing urban planners and policy makers achieve better functionality of cycling network and its integrity with urban green infrastructure.
The main research questions are: (a) how actively used cycling routes correlate with the distribution of green infrastructure segments? And (b) which urban green spaces need to be considered by Prague municipalities and urban planning practitioners in order to better integrate them with the cycling network and create safer environments for non-motorized modes of mobility?

Methodology

The work is based on the combination of geospatial analysis along with qualitative and semi-quantitative research methods. Geospatial analysis involves visualization of geographic information system (GIS) data that indicate Prague urban green spaces as well as planned and present network of cycling routes. All datasets are divided and categorized by author according to types, accessibility, and qualities of both cycling and green infrastructures. In order to depict and assess routes that are in fact used by bicyclists two main data sources are used:

- Unicam camera traps used as bike counters installed across the city as a part of Golemio data platform run by Operator ICT in the framework of Smart Prague concept;

- heatmaps and analyses of bicycling intensity that originate from the data derived from multiple GPS records such as those made by participants of Bike to Work (‘Do práce na kole’) annual campaigns run by AutoMat NGO and Umotional s.r.o. as the part of Zero-Emission Prague's communication campaign for sustainable mobility ('Čistou stopou').

These open datasets enable the author to identify and analyze cycling routes actively used by local bicyclists and depict them along with the data that illustrates the distribution of urban green spaces. For instance, the data from Golemio camera traps is represented in the form of tables and GIS shapefile, created by author, and illustrates the intensity of riding in fixed locations during active cycling seasons (April to September) throughout the period of three years (2018-2020). Based on the comparison of actual routes used by local cyclists and spatial distribution of green spaces, the author highlights the gaps in Prague cycling infrastructure and suggests improvements that might lead to enhanced connectivity and safety of cycling paths as well as functionality and its integrity with urban green infrastructure.

The combination of data indicating (a) present and planned bicycling routes, (b) urban green infrastructure settings, and (c) actual spatial distribution of cycling activity should help local authorities better distribute the investments in both cycling and green infrastructure of the city and enhance safety of infrastructure suitable for non-motorized modes of mobility.

The whole research involves geospatial analysis and geographic visualization of urban green infrastructure and cycling routes along with a combination of semi-quantitative and qualitative research of factual spatial distribution of bicycling activity in Prague.

The proposed extent of the thesis

65 pages

Keywords

urban green infrastructure; urban green spaces; ecosystem services; geospatial analysis; GIS; green cycling routes; non-motorized mobility; sustainable landscape planning; urban planning; bicycling; connectivity; quality of green spaces; greenways; sustainable transportation

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Author’s Declaration:

I hereby declare that the work presented in this thesis entitled “Spatial distribution of urban green infrastructure and bicycling activity in Prague: integrity, connectivity, and functionality” is original and done by me independently, under the direction of doc. Peter Kumble. I have listed all literature and publications from which I acquired information in the attached list of references at the end of the thesis.

In ___________ on ___________ ____________________

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Abstract

The following work is focused on two systems associated with urban green infrastructure: green spaces and cycle routes. It aims to identify interrelation between green and cycling infrastructures of Prague in terms of their spatial distribution and qualitative elements. The goal is to determine and classify structural qualities typical for major green spaces in terms of intensity of their use by cyclists. The study intends to contribute to the development of conditions created for non-motorized users through the enhanced connectivity and safety of cycle routes and traffic-free paths that are often associated with urban green infrastructure. Using geospatial analysis and geographic information system (GIS) morphological features of green spaces and characteristics of designated cycle routes are determined and evaluated. Besides, a semi-quantitative research of frequently used bikeways is executed to indicate the preferences of local cyclists in terms of cycling conditions. This work is meant to help urban planners achieve better functionality and integrity of green spaces and cycling infrastructure.

Key words: green infrastructure, urban green spaces, non-motorized mobility, cycling infrastructure, sustainable transportation

Abstrakt

Následující práce se zaměřuje na dva systémy týkající se městské zelené infrastruktury: zelené plochy a cyklostezky. Jejím cílem je identifikovat vzájemné vztahy mezi zelenou a cyklistickou infrastrukturou Prahy z hlediska jejich prostorového rozložení a kvalitativních aspektů. Cílem je stanovit a klasifikovat strukturální vlastnosti typické pro významné zelené plochy z hlediska intenzity jejich využívání cyklisty. Studie míní přispět k rozvoji prostředí vytvořeného pro nemotorizované uživatele prostřednictvím posílení konektivity a bezpečnosti cyklotras a stezek bez automobilové dopravy, které jsou často spojovány s městskou zelenou infrastrukturou. Pomocí geoprostorové analýzy a geografického informačního systému (GIS) jsou určeny a vyhodnoceny morfologické vlastnosti zelených ploch a charakteristiky značených cyklostezek. Kromě toho je proveden semikvantitativní průzkum často používaných cyklostezek s cílem určit preference zdejších cyklistů z hlediska podmínek pro jízdu na kole. Tato práce má urbanistům pomoct dosáhnout lepší funkčnosti a integrity zelených ploch a cyklistické infrastruktury.

Klíčová slova: zelená infrastruktura, městská zeleň, bezmotorová mobilita, cyklistická infrastruktura, udržitelná doprava

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1. Introduction

According to Husqvarna Urban Green Space Index, which intends to quantify and analyze urban green spaces with the use of computer vision applied on satellite images, Prague is ranked 13th out of 155 assessed cities with almost 180 m^2 of green space per capita (HUGSI, 2021). Various types of green spaces have been a part of the urban landscape of Prague for centuries and today they are presented in different forms and shapes. They constitute an inner recreational potential of the city which tends to improve a quality of life of its citizens. The variety of green spaces in Prague ranges from the 18th century Baroque gardens in the historic neighborhoods to large public woodlands that are not only used for recreation by local dwellers, but function as crucial regional biocenters.

Nonetheless, apart from recreation, the presence of green infrastructure in the cities affects multiple essential attributes of ecological stability such as air and water quality, local climate, and many others (MEA, 2005). The definition of green infrastructure is still somewhat controversial due to its universality and a wide use in different fields of study. The term is commonly used in such disciplines as urban planning and landscape architecture along with environmental management and bioconservation. Besides, even at a city scale the perception of green infrastructure might differ from green open spaces to street trees or green roofs. Hence, the use of the term ‘urban green infrastructure’ depends on the context and objectives of study.

The variety and ubiquity of green infrastructure creates possibilities to study it and its functions in different terms and scales. Some similar features may be found in the studies of green infrastructure executed at different scales. For instance, the landscape mosaics model usually associated with landscape ecology has also been applied in the context of urban environment and morphology of its elements (Ahern, 2007). The model suggests that landscape elements in terms of their structure and functions can be divided under the patches-corridors-matrix system. Such an approach correlates with an acknowledged classification of green infrastructure stating that in terms of a physical form the network consists of hubs, links, and sites (Benedict & McMahon, 2006).

Besides, It is common to classify the functions of green infrastructure in three dimensions that can be generalized as abiotic, biotic, and cultural groups of functions (Ahern, 1995). Also, the number of functions of the green environment frequently happen to be referred to as ‘ecosystem services’, which are more likely to consider green infrastructure from the perspective of human beneficiary (Chan et al., 2006).

Nevertheless, it is evident that green infrastructure and its qualities are directly and indirectly affect the quality of life of people residing by. In contrast to green infrastructure in rural areas and natural environments, the direct functions of green infrastructure associated with densely populated urban areas are more often represented in social and cultural dimensions, particularly in recreation, aesthetics, social cohesion, etc. (Gómez-Baggethun et al., 2013). The level of prevalence of physical activity as part of recreation of citizens and its interrelation with the environment has been a subject of study in many fields, particularly in public health, transport and urban planning, recreation and leisure sciences (Wahlgren, 2011).

Nonetheless, globally the number of studies aimed to perceive or evaluate the interrelation between non-motorized transportation as part of physical activity and availability or arrangement of green infrastructure in urban areas is comparatively low. The subject of interrelation between elements of green infrastructure and non-motorized mobility in terms of recreation and transportation does not seem to gain much attention in Prague either, despite a relatively large presence of green spaces. Furthermore, infrastructure for non-motorized modes of transport is usually assessed from the perspective of technical solutions and qualities of hard infrastructure rather than its interrelation with green infrastructure and possibilities to create safer routes segregated from motor traffic through the improved connectivity of routes and green infrastructure segments.

It is suggested by the author that availability and qualities of green spaces in urban areas can have an impact on the popularity of cycling as part of physical activity in terms of transportation or recreation. For this reason, the systems of green and cycling infrastructure of Prague were chosen to be analyzed and compared in the present thesis.

2. Objectives of Study

The study intends to characterize the interrelationship between spatial distribution of green and cycling infrastructures in Prague. The first part of work includes a comprehensive review of literature and research projects about green infrastructure, particularly in urban environments, ecosystem services it delivers, and its possible connections with physical activities among the population, including bicycling as the most ubiquitous type of non-motorized mobility.

The second part of study is represented by analysis of cycling conditions and arrangement of cycle routes, assessment of green infrastructure in terms of distribution of different types of its elements, accessibility, and terrain. The level of connectivity between segments of cycling infrastructure and green spaces is evaluated and represented by the maps.

Geographic information system (GIS) analysis is used to map the distribution and indicate the qualities of both green and cycling infrastructures. The goal is to determine the attributes typical for urban green spaces and cycle routes in Prague. With respect to landscape ecology principles and based on a spatial configuration of major green spaces and their functions in terms of cycling an attempt to categorize them is made. The intensity of use of different categories of designated bikeways is also assessed and depicted on maps in order to identify gaps in the system of cycle routes and analyze functionality of the network.

Comprehension of qualitative elements of both systems of green and cycling infrastructures should help urban planners and policy makers achieve better functionality of the network of cycle routes and its integrity with urban green spaces. Besides, the safety of cycling infrastructure and connectivity of safe cycle routes that exclude motor traffic can be improved, enabling a wider range of people to use it as non-motorized users.

The study involves geospatial analysis and geographic visualization of urban green infrastructure and network of bikeways along with a combination of semi-quantitative and qualitative research methods used to identify and evaluate a factual arrangement of cycle routes in Prague.

3. Literature Review

3.1 Contemporary perception of green infrastructure and its elements

Over the past decades multiple studies in the fields of environmental science, landscape and urban planning, public health and human well-being have addressed and used the concept of green infrastructure (Benedict & McMahon, 2006; Ahern, 2007; Mell, 2010; Austin, 2014; Elmqvist et al., 2015; Pulighe et al., 2016). The topic has become the focus of increasing interest in a wide range of fields, so the relevance of the concept appears to be of high level. A significant number of disciplines associated with green infrastructure and its multifunctional character created numerous ways to define and understand the concept. The European Environment Agency (EEA) suggests grouping the definitions of green infrastructure under two concepts with respect to their scale: (a) green infrastructure at urban scale, and (b) at landscape scale (regional, national and transnational) (EEA, 2011).

The present research is focused on green infrastructure in Prague urban area and its possible impact on the development of bicycling activity in the city, thus the concept of green infrastructure is considered predominantly in terms of urban scale. However, the landscape scale is essential to be described and understood if one aims to have a comprehensive picture of green infrastructure and its values for humans. A range of definitions of green infrastructure conceived by different authors representing various scales and obstacles is listed and discussed in the following chapter.

3.1.1 Multifunctional character and complications in defining green infrastructure

Green infrastructure as a term has been adopted by different disciplines related to conservation, design and planning. Nevertheless, it is possible to designate specific underlying features that are common to most of the fields of study that use the term. Those are *connectivity*, *multifunctionality* and *smart conservation* (EEA, 2011). The majority of studies generally aim to either protect or develop green infrastructure networks, thus it can also be determined as a common feature (EEA, 2011).

As previously mentioned, various concepts of green infrastructure can be grouped under urban and landscape scales. Table 3.1.1 presents a description and comparison of the scales of green infrastructure definitions as regarded by the European Environment Agency Technical Report (EEA, 2011).

Besides scale differences, green infrastructure definitions in various literature sources refer to different concepts and processes. For example, Benedict and McMahon (2006), using a green infrastructure term as a noun, describe it as *‘an interconnected green space network that is planned and managed for its natural resource values and for associated benefits it confers to human populations’*. Using the term as an adjective, the authors regard green infrastructure as *'a process that promotes a systematic and strategic approach to land conservation at the national, state, regional and local scales, encouraging land-use planning and practices that are good for nature and for people'* (Benedict & McMahon, 2006).

Table 3.1.1: Comparison of green infrastructure at urban and landscape scales based on various definitions (Credits: EEA, 2011)

Green infrastructure characteristics	Urban scale	Landscape scale
Short description	- Development and protection of a network of multifunctional green space in urban environments	- Development and protection of connections between valuable habitats in wider landscape scale
Matrix / obstacles	- Urban built-up environment	- Intensively farmed land - Built-up areas - Grey infrastructure
Key associated benefits (as highlighted in the literature)	- Urban heat island mitigation - Water run-off management - Water retention (flood prevention) - Recreation - Visual pleasure, sense of nature and open space - Wildlife habitats	- Species migration - Water retention (water recharge and flood prevention) — to a lesser extent
Most common structures	- Parks, tree-lined avenues, green roofs, agricultural land and woodland inside towns, etc.	- Habitats (in the EU, more specifically the Natura 2000 sites) and corridors - Rivers and streams, hedges, etc. - Overlap with term 'ecological network'
Examples of disciplines using the term	- Urban planning - Landscape architecture - Environmental management	- Species conservation - Spatial planning - Environmental management
Key topic / policy links	- Quality of life in cities - Biodiversity protection - Climate change adaptation - Climate change mitigation	- Biodiversity protection - Climate change adaptation

In the context of a green space network concept, the definition emphasizes conservation as a key benefit of green infrastructure and refers primarily to a landscape scale. Planning and management of a green infrastructure network may be used to conduct the creation of the assets that support conservation as well as associated outdoor activities and other human values (Benedict & McMahon, 2006). Using the concept of green infrastructure as a process allows the creation of a mechanism for diverse interests in order to identify priority lands for protection. This way, definition emphasizes a green infrastructure through a multi-scale approach and may be used, for instance, in urban planning (Benedict & McMahon, 2006). However, the general definition of green infrastructure framed by the authors considers it as a network of natural areas and open spaces on a rather landscape scale (Table 3.1.2).

A range of various definitions and explanations of green infrastructure occurring in present literature creates complications of its apprehension through emphasizing different things and at different scales. In the reports various governmental environmental organizations emphasize the multifunctionality of green infrastructure as well as a vast range of functions and ecosystem services they deliver (Table 3.1.2) (EEAC, 2009; Landscape Institute, 2009; Forest Research, 2010; Natural England, 2010; EEA, 2011; European Commission, 2013).

Table 3.1.2: Examples of green infrastructure definitions

Reference	Explanation	Scale of application
Benedict and McMahon (2006)	Green infrastructure is an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife.	Landscape
European Environment Agency (2011)	Green infrastructure is a concept addressing the connectivity of ecosystems, their protection and the provision of ecosystem services, while also addressing mitigation and adaptation to climate change. Green infrastructure helps ensure the sustainable provision of ecosystem goods and services while increasing the resilience of ecosystems.	Landscape
Landscape Institute (2009)	Green infrastructure is an approach to land use, underpinned by the concept of ecosystem services. Green assets such as parks, coastlines or embankments have generally been thought of in terms of their single functions — the approach that recognises their vast range of functions and their interconnectivity is called green infrastructure.	Landscape / Multi-scale
Tzoulas et al. (2007)	The concept of Green Infrastructure can be considered to comprise all natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas, at all spatial scales.	Multi-scale
European Commission (2013)	Green Infrastructure can be broadly defined as a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings.	Multi-scale
Forest Research (2010)	Green infrastructure refers to the combined structure, position, connectivity and types of green spaces which together enable delivery of multiple benefits as goods and services. It is important to consider green infrastructure holistically and at landscape as well as individual site scale.	Multi-scale
Natural England (2010)	Green infrastructure is a strategically planned and delivered network of high-quality green spaces and other environmental features. It should be designed and managed as a multifunctional resource capable of delivering those ecological services and quality of life benefits required by the communities it serves and needed to underpin sustainability. Green infrastructure includes established green spaces and new sites and should thread through and surround the built environment and connect the urban area to its wider rural hinterland.	Urban

Ahern (2007)	Green infrastructure is a concept that is principally structured by a hybrid hydrological/drainage network, complementing and linking relict green areas with built infrastructure that provides ecological functions. Green infrastructure plans apply key principles of landscape ecology to urban environments.	Urban
Sandström (2002)	‘Green infrastructure’ concept is introduced in order to emphasize the multiple purposes of green space (including ground and surface water). In current efforts to achieve sustainable urban development, ‘green infrastructure’ has the same dignity as ‘technological infrastructure’ has had in traditional urban planning.	Urban
EEAC (2009)	Green infrastructure is the actions to build connectivity nature protection networks as well as the actions to incorporate multifunctional green spaces in urban environment.	Urban

To highlight the association between green infrastructure and ecosystem services the Technical Report of the European Environment Agency mentions that investigation illustrates the evidence of the synergy between the two (EEA, 2011). The Landscape Institute also underpins the concept of ecosystem services in terms of multifunctional nature of green infrastructure assets (Landscape Institute, 2009). The relations between green infrastructure, its benefits and ecosystem services are discussed in detail in Chapter 3.3 of the present work.

The definition presented in the Green Infrastructure Guidance by Natural England generally considers green infrastructure on urban scale simultaneously highlighting ecological services and quality-of-life benefits that green spaces provide to communities (Natural England, 2010). Some studies and articles particularly underscore the importance of considering green infrastructure on various scales (Tzoulas et al., 2007; Forest Research, 2010; European Commission, 2013).

Some definitions refer to green infrastructure as a network emphasizing connectivity as an important attribute whether considering it as a concept or planning approach. Regardless of scale, few definitions mention that a green infrastructure network is required to be strategically planned and comprise high-quality green spaces (Natural England, 2010; European Commission, 2013).

The definitions of green infrastructure framed by Sandström (2002) and Ahern (2007) generally refer to it on an urban scale emphasizing the connection of green spaces with hydrological components, particularly drainage network, ground and surface water. Moreover, Sandström (2002) states that green infrastructure has the same status as technological infrastructure has had in urban planning.

Although research by Sandström (2002) emphasizes green infrastructure planning in the urban areas of Sweden, such interpretation has been repeatedly used in American science since the mid 1990’s, when the term was used for the first time. Geographic analysis of the definitions of green infrastructure shows that in the United States the concept is often applied to the management of stormwater run-off through the use of natural systems (EEA, 2011). However, some American institutions like the

Conservation Fund use the term in its broader meaning, also recognizing the benefits of green infrastructure (e.g. Benedict & McMahon, 2006).

“American” perception of green infrastructure as a network of hydrological components is also typical for Ahern (2007), who particularly focuses on the application of landscape ecology principles to urban green infrastructure, while the spatial configuration of it is the point of integration. The author claims that the key ideas from landscape ecology like multi-scale approach and emphasis on physical and functional connectivity are of high relevance for urban green infrastructure (Ahern, 2007). The examples of urban landscape elements classified in the patch-corridor-matrix model from applied landscape ecology are presented in Chapter 3.2.

Similarly to the definition by Ahern (2007), the explanation of green infrastructure by Tzoulas et al. (2007) emphasizes the holistic ecosystem vision of urban environment. While that work considers the concept of green infrastructure as *‘a comprise of all natural, semi-natural and artificial networks of multifunctional ecological systems’*, the study by Ahern (2007) pays particular attention to abiotic, biotic and cultural functions that can be provided by urban green infrastructure. Both studies highlight the importance of multi-scale approaches that consider the scale-dependent relationships of ecological processes (Pulighe et al., 2016).

Essentially, the present work adopts the definition of green infrastructure proposed by Ahern (2007) who describes the nature of green infrastructure on urban scale connecting green areas with hydrological and drainage objects and highlighting spatial dimensions of urban green infrastructure. However, the definitions framed by Tzoulas et al. (2007) and Natural England (2010) are also considered as fitting the objectives of present work.

3.1.2 Categorizing and planning of green infrastructure

Regardless of scale, green infrastructure encompasses a wide range of natural and semi-natural or restored ecosystems and landscape features. According to Benedict and McMahon (2006), a green infrastructure network as a physical form connects these ecosystems and landscapes in a system of *hubs, links,* and *sites* (Figure 3.1).

Hubs are the anchors of green infrastructure networks that provide habitats and space for native plants and animal communities. They may be represented in all shapes and scales and encompass various systems, for instance:

- reserves and protected areas, such as national wildlife refuges and state parks;
- large publicly owned lands, such as national and state forests;
- private working lands, such as farmlands and forests;
- regional parks and reserves;
- community parks and green spaces (Benedict & McMahon, 2006).

Natura 2000 is the largest coordinated network of protected areas in the European Union that incorporates valuable habitats and threatened species and habitats

(European Commision, 2013). In terms of EU biodiversity protection and nature conservation many sites assigned to Natura 2000 might be considered as green infrastructure hubs.

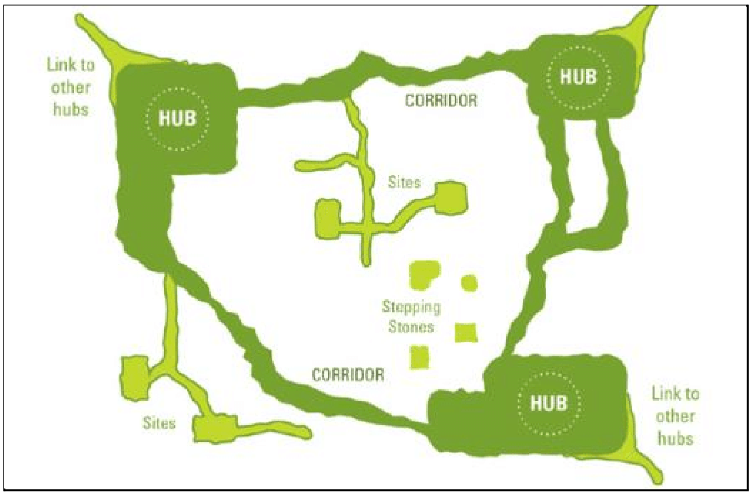


Figure 3.1: Components of green infrastructure network (Credits: Diamond Head Consulting, 2014)

Sites are another important component of a green infrastructure network at both urban and landscape scales. They contribute ecological and social values, such as protecting wildlife habitat and providing space for nature-based recreation. Sites are smaller than hubs and not always connected to a larger community or regional conservation systems (Benedict & McMahon, 2006).

The crucial features of green infrastructure network systems are the links. They tie all the components of green infrastructure together and are essential for maintaining vital ecological processes and biodiversity of wildlife populations (Benedict & McMahon, 2006). Links are linear features that may be divided into *landscape linkages* and *conservation corridors*. Landscape linkages are especially long and wide links that connect existing parks, preserves, or natural areas. They serve as corridors connecting ecosystems and landscapes that also provide opportunities for recreational use. The so-called conservation corridors include river and stream floodplains and perform the functions of biological canals for wildlife as well as provide opportunities for outdoor recreation (Benedict & McMahon, 2006).

Besides distinguishing a green infrastructure as a system of hubs, links and sites, all its elements can be related to various physical components that make up the integral parts of a network. The Landscape Institute (2009) generally describes these elements as the green infrastructure assets. Green infrastructure assets are regarded as *'the natural elements that provide social, environmental and economic benefits and include specific sites or broader environmental features within and between rural and urban areas'* (Landscape Institute, 2009). Based on hierarchical scales they are grouped under three broad categories:

- local, neighborhood and village scale;
- town, city and district scale;
- city-region, regional and national scale (Landscape Institute, 2009).

To a certain extent such a classification of the assets correlates with a grouping of green infrastructure definitions with respect to scales presented by the EEA (2011) and mentioned above. One may consider the *‘City-region, regional and national scale’* by the Landscape Institute (2009) as the *‘Landscape scale’* by the EEA (2011), while *‘Local, neighborhood and village scale’* as well as the *‘Town, city and district scale’* generally may be referred to the *‘Urban scale’* category of definitions. The classification of green infrastructure assets presented by the Landscape Institute (2009) is perhaps one of the most comprehensive lists of green infrastructure components and their potential assets (Table 3.1.3).

Table 3.1.3 Typical green infrastructure assets and their associated scales (Credits: Landscape Institute, 2009)

Local, neighborhood and village scale	Town, city and district scale	City-region, regional and national scale
● Street trees, verges and hedges ● Green roofs and walls ● Pocket parks ● Private gardens ● Urban plazas ● Town and village greens and commons ● Local rights of way ● Pedestrian and cycle routes ● Cemeteries, burial grounds and churchyards ● Institutional open spaces ● Ponds and streams ● Small woodlands ● Play areas ● Local nature reserves ● School grounds ● Sports pitches ● Swales, ditches ● Allotments ● Vacant and derelict land	● Business settings ● City/district parks ● Urban canals ● Urban commons ● Forest parks ● Country parks ● Continuous waterfronts ● Municipal plazas ● Lakes ● Major recreational spaces ● Rivers and floodplains ● Brownfield land ● Community woodlands ● (Former) mineral extraction sites ● Agricultural land ● Landfills	● Regional parks ● Rivers and floodplains ● Shorelines ● Strategic and long distance trails ● Forests, woodlands and community forests ● Reservoirs ● Road and railway networks ● Designated greenbelt and strategic gaps ● Agricultural land ● National parks ● National, regional or local landscape designations ● Canals ● Common lands ● Open countryside

Recently the classification of green infrastructure became a necessity for practitioners and policy makers for assessing current conditions and planning future development scenarios (Bartesaghi Koc et al., 2017). Based on terminology and definitions of green infrastructure used in 85 studies from 15 countries Bartesaghi Koc et al. (2017) claim that the majority of green assets can be grouped under four main categories: (a) tree canopy; (b) green open spaces; (c) green roofs; and (d) vertical greenery systems (e.g. green walls and facades). The terminology that has been used in different studies to refer to different green infrastructure assets is illustrated in Table 3.1.4.

Table 3.1.4 Different terminology associated with main categories of green infrastructure (Credits: Bartesaghi Koc et al., 2017)

Tree canopy (TC)	Green open spaces (GOS)	Green roofs (GS)	Vertical greenery systems (VGS)
Green canopy Green streets Green alleys [Street] Trees Shrubs, shrubbery Tree cover Urban forestry Urban tree canopy Woodland [Forest]land	Green belts Green corridors Green covers Greenspaces Greenways [Vegetated] Ground covers Ground surfaces Land covers [Public] [Urban] open spaces Urban land [Urban] vegetation structures Vegetative covers	Eco-roofs Green rooftops Living roofs Rooftop gardens	Bio-walls Green facades Green walls Living walls Vertical landscaping Vertical vegetation

Bartesaghi Koc et al. (2017) also acknowledge that the scope and scale of analysis of green infrastructure are essential for distinguishing different typologies. For instance, predominantly naturally created categories such as tree canopy and green open spaces have been reviewed from regional to street canyon scale, while green roofs and vertical greenery systems as man-made engineered constructions have been studied mainly on the street canyon and building scales (Figure 3.2). Authors summarize that *'the coarser the scale the more generalised and difficult is to discern individual elements and their spatial arrangements'* (Bartesaghi Koc et al., 2017).

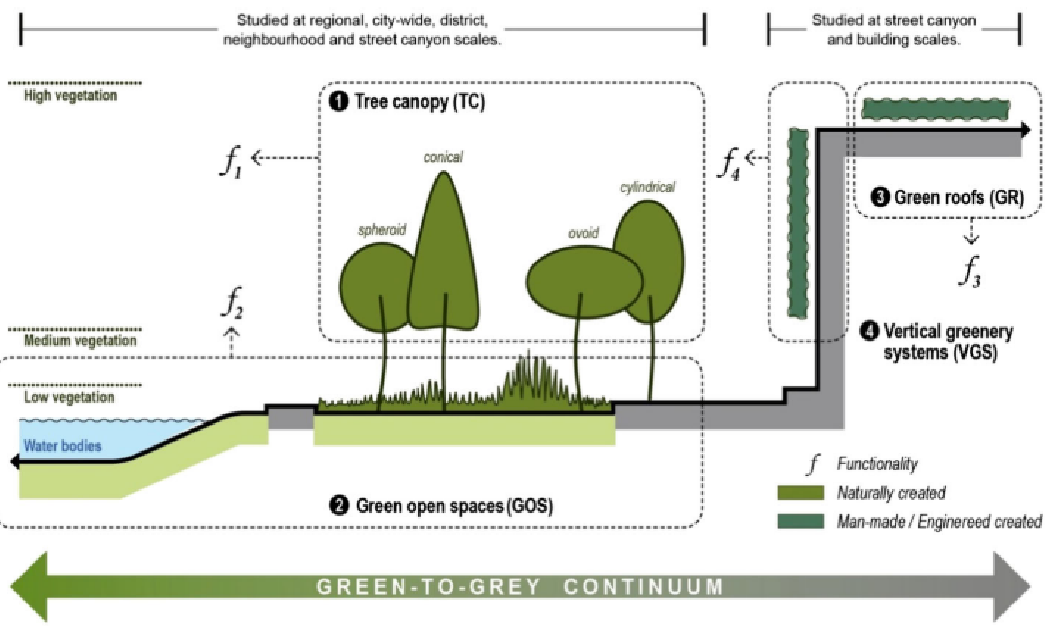


Figure 3.2 Spatial conception for the identification of main green infrastructure categories in a green-to-grey spectrum (Credits: Bartesaghi Koc et al., 2017)

In the study that aims to classify greenways Ahern (1995) outlines three key areas that can be considered central in the scientific debates over green infrastructure: (a) scale; (b) spatial context; and (c) landscape functionality. Based on this classification Mell (2010) proposes a refined typology that defines how green infrastructure fits in the following areas: (a) form; (b) context; and (c) function. Author suggests that each of these areas can be reviewed over ecological, economic and social criterias (Table 3.1.5).

Table 3.1.5 Green infrastructure typology classifications by Mell, 2010

Typology classification	Element or function
Form	**Ecological:** physical space, connectivity, elements **Economic:** costs of space, design **Social and cultural norms:** users of a space, aesthetics of a space, motivations
Function	**Ecological:** biodiversity, conservation **Economic:** industry, business, regeneration **Social:** education, recreation, health
Context	**Ecological:** biodiversity, supporting networks, ecological mobility **Economic:** costs of space, economic development, sustainability **Social and cultural norms:** location, facilitations, motivations, perceptions

In line with tripartite approaches by Ahern (1995) and Mell (2010), the study of Bartesaghi Koc et al. (2017) suggests that green infrastructure can be classified with respect to three main principles: (a) functional (services); (b) structural (morphology); and (c) configurational (spatial interrelationships). Thus, based on methods, approaches, and parameters used by evaluated studies, authors present two perspectives on how green infrastructure can be classified: *functional-configurational* and *structural-configurational* (Table 3.1.6).

Bartesaghi Koc et al. (2017) estimate that functional-configurational classification type has been a more common approach to categorize green infrastructure. However, structural characteristics of vegetation have also been a common principle for classifications of green infrastructure. The identification of the physical and formal attributes of green infrastructure has been emphasized in the studies concerning tree canopy, green roofs and vertical greenery systems, while, for instance, land and vegetation cover classifications have been used mainly to record tree canopy and green open spaces (Bartesaghi Koc et al., 2017).

Besides categorizing green infrastructure and its assets, strategic planning and maintenance of green infrastructure are another concern for researchers and practitioners across various fields. Contemporary urban planning and design literature often addresses sustainable cities and urbanism. Ahern (2007) suggests that sustainability, in broad terms, can be reflected in three dimensions: economic, social, and environmental. These tripartite dimensions are often referred to as *"three E's"* of sustainability, where E's stand for economy, environment and (social) equity (Wheeler & Beatley, 2002).

Table 3.1.6 Parameters used by studies from two classification perspectives (Adapted from Bartesaghi Koc et al., 2017)

Functional-configurational classification	Structural-configurational classification
1. Size 2. Location & catchment 3. Scale & hierarchy 4. Spatial configuration & complexity 5. Land-use types 6. Purpose 7. Significance 8. Accessibility & ownership 9. Management & maintenance 10. Intensity of intervention/use 11. Functions & values: a. Socio-cultural b. Economic c. Environmental d. Political 12. Ecosystem services: a. Provisioning b. Regulating c. Cultural d. Supporting	1. Land-use/land cover (LULC) types 2. Spatial scale 3. Urban morphology types 4. Vegetation attributes a. Foliage geometry & shape b. Foliage contiguity & distribution c. Foliage density dimensions / volume d. Foliage type e. Extension & orientation f. Segment attributes of trees g. Derived fractions of vegetation h. Thermal properties of plants 5. Surface properties: a. Biological b. Physical & thermal c. Structural 6. Supporting structure attributes (for green roofs and vertical greenery systems only): a. Construction materials b. Installation c. Location & orientation d. Operation & maintenance e. Intensity of use f. Accessibility

According to Tzoulas et al. (2007) the modern perception of the green infrastructure concept on urban scale includes the quality and quantity of urban and peri-urban green spaces, their multifunctional role and the importance of interconnection between habitats. Strategically planned urban green infrastructure can offer multiple opportunities for integration between sustainable urban development, nature conservation and public health promotion.

The sustainable development concept has gained great international acceptance, thus has progressively influenced regional and municipal planning. For this reason Benedict and McMahon (2006) have determined ten principles of green infrastructure planning that can be used as benchmarks for integrating a green infrastructure approach into existing planning traditions, regardless of scale. The list of these principles is outlined and explained in Appendix 1 of the present work.

With respect to aims of present thesis and its focus on bicycling network development based on continuity and connectivity of green infrastructure network the particular attention is paid to principles 1 (*'Connectivity is key'*), 2 (*'Context matters'*), 7 (*'Green infrastructure affords benefits to nature and people'*), and 9 (*'Green infrastructure requires making connections to activities within and beyond communities'*). For more details see Appendix 1.

In general terms, all ten principles specified by Benedict and McMahon (2006) are essential pillars for successful green infrastructure planning. Depending on scales and aims of green infrastructure initiatives the role of different principles can vary, although none of them should be neglected or ignored.

3.2 Urban green structures and their qualities

As previously mentioned, many authors define green infrastructure at the urban scale and in terms of urban environment. Urban green infrastructure has been a subject for research in various fields for a long time. In the early 1960's Philip Lewis became the first to use the overlays in order to assess natural and perceptual resources. Using the United States Geological Survey (USGS) maps, he delineated water objects, wetlands and significant topography patterns that make up, as he refers, *'environmental corridors'* and *'landscape personalities'* (Ndubisi, 2002).

In 1969 Ian McHarg mentioned the need for urban planners to consider environmentally conscious approaches to land use. In his seminal book *Design with Nature* he also claims that natural processes should be a core for determining development priorities (McHarg, 1969). McHarg promoted ecology as the foundation science for landscape architecture and regional planning. He also became the first to use map overlays to quantify and display the spatial data of New York City urban area in order to show the importance of environment in land-use planning and urban design (Benedict & McMahon, 2006). This method of superimposing the maps has become known as *'suitability analysis'* and it explicitly linked ecology to planning and design and is being used by practitioners and scholars today (Ndubisi, 2002).

Academic attention to urban green structures increased particularly in the 1990's along with the perception of pressure on natural resources and the environment that urbanization implies. It was in 1996 when the European Commission claimed that open green spaces are as important as buildings and physical infrastructure (Sandström, 2002).

The following section aims to present an overview of contemporary studies of urban green structures and green open spaces, including their key functions and components.

3.2.1 Modern perception of green infrastructure and green open spaces in urban areas

Cities are complex ecological entities that involve various rules and dynamics of growth, behaviour and evolution, which result from dynamic interactions between biophysical and socioeconomic forces (Alberti et al., 2003). Rapid urbanization in the recent decades along with increasing pressure on the environment that affects urban biodiversity, local climates and water regimes, has resulted in the increased attention to urban green spaces and the ways they can benefit cities and their inhabitants (Sandström, 2002). The EU study that aims to develop new concepts for integration of Natura 2000 network defines urban green infrastructure as *'a spatial network that* *links open spaces, public and private gardens and parks, sportfields, allotment gardens and recreational grounds within the city and its linkage to the networks of woodlands and river floodplains in the surrounding countryside'* (European Commission, 2007).

Traditionally, the concept of urban green infrastructure has been used for parks and other natural or semi-natural spaces in urban areas where recreation plays the main role (Sandström, 2002). However, during the past decades studies have shown that urban green infrastructure comprises multiple functions and benefits (Chiesura, 2004; Ahern, 2007; Jansson, 2014; Elmqvist et al., 2015). Urban green structures provide a vast set of ecological, economic and social benefits that lead to improved livability, quality of life and sustainability of urban areas (Quintas & Curado, 2010).

Sandström (2002) suggests that various uses of urban green spaces can be roughly divided into six classes: (a) *aesthetic* (e.g. historical gardens); (b) *functional* (e.g. for leisure, health, and education); (c) *ecological* (e.g. habitat for flora and fauna); (d) *technical* (e.g. storm water management); (e) *symbolic* (e.g. green spaces as a symbol of the city); (f) *speculative* (e.g. as a resource for urban exploitation). Such a categorization comprises both ecological and social aspects of the functions of urban green infrastructure. However, as long as the pressure on natural resources implied by urbanization increases the ecological set of functions will remain one of the main subjects for research.

Green open spaces as a category of urban green infrastructure seem to gain the most attention from academia. The literature overview by Bartesaghi Koc et al. (2017) has shown that green open spaces were mentioned in roughly 74% of assessed papers. Similarly, according to Pulighe et al. (2016), 'urban green spaces' along with 'urban trees' are the most frequently mentioned green infrastructure categories across the studies of mapping approaches of urban ecosystem services. Bartesaghi Koc et al. (2017) suggest that green open spaces have attracted so much attention due to their role in planning strategies and interventions.

Over the last century green areas became an essential component of urban planning that seeks to improve climate conditions, hygiene, aesthetics, create recreational opportunities, protect the environment and biodiversity (Ignatieva et al., 2011). Nonetheless, categorizing the components of green open spaces has been a subject for scientific debates for a while. Similarly to the classification of green infrastructure stemmed from a scale, many studies essentially distinguish green open spaces into those within urban cores and those beyond the urban periphery studied predominantly at local and meso scales (Bartesaghi Koc et al., 2017).

According to Bartesaghi Koc et al. (2017), the classification of green spaces are basically linked to land-uses, purposes, functions, hierarchy, and connectivity. Based on the literature overview, authors present the typologies that have been identified and used by different assessed studies. The one used by most of them is illustrated in Table 3.2.1.

Table 3.2.1 Most used typologies of green open spaces (Adapted from Bartesaghi Koc et al., 2017)

According to:	Typology
The purpose:	1. Parks and gardens: country, urban and local parks, public & private gardens, courtyards 2. Natural & semi-natural green spaces: woodlands, forests, reserves, heathlands, grassland, meadow, conservation land 3. Greenways, green corridors, ecological buffers, green streets/alleys, green wedges, cycle paths, pedestrian trails, routes 4. Wetlands: marshlands, intertidal mudflats 5. Brownfield land: quarries, wastelands, landfills, vacant and derelict land 6. Amenity green spaces: recreation grounds, sport fields/facilities, golf courses, playgrounds, racecourses 7. Community green spaces: allotments, community gardens, orchards 8. Waterbodies and waterside areas: coasts, beaches, seafronts, rivers, canals, ponds, lakes, estuaries, swales, ditches 9. Green links, utility areas: roads, rails, power lines, drainage-ways, transport corridors 10. Agricultural land, farms, ranches 11. Landscaped and incidental areas 12. Churchyards, cemeteries, burial grounds 13. Institutional grounds 14. Civic spaces: squares, plazas, malls, foyers 15. Built-up areas residential land, multistorey buildings, mixed uses, construction sites
The scale and location:	1. Urban periphery a. National-regional ● Patches, corridors, matrixes 2. Urban cores a. City-district b. Neighbourhood 3. Local / parcel
Accessibility/ ownership:	1. Unrestricted 2. Limited 3. Not accessible

Compared to other types of green infrastructure (tree canopy, green roofs, vertical greenery systems) green open spaces is the most relevant category of urban green infrastructure in terms of present study. Such criteria of green infrastructure as land use and land cover, accessibility, functions and values of green space as well as other parameters particular for functional-configurational classification of green infrastructure (Table 3.1.6) are important for meeting the objectives and goals of the present work.

3.2.2 Structure and functions of urban green infrastructure

Sustainable urban planning requires considering uses and benefits of urban green infrastructure at a wider scope, while taking account of all the functions and components of urban green spaces. Key principles and theoretical perspective of landscape ecology applied to urban green structures at different scales and from various perspectives can help achieve full-fledged sustainable development of urban areas. There are many theories and models from landscape ecology that are relevant to urban green infrastructure and can be applied to a spatial configuration of urban green structures and their components (Ahern, 2007).

Like any other system, urban green infrastructure has a function and a structure. Landscape ecology theories and analytical tools can be applied to urban areas in order to understand the complexity and diversity of urban environment functions with respect to specific ecological processes (Pickett et al., 2004). For instance, one of the concepts that aims to deliver the maximum level of ecological functions is an ecological network approach, which has been implemented worldwide, although predominantly at broad scales (Jongman & Pungetti, 2004). The green infrastructure movements, particularly urban green infrastructure, changes the focus of ecological network concept from international and regional levels, while seeking to apply it to urban contexts (Ahern, 2007).

Ahern (2007) emphasizes the importance of spatial configuration in terms of integration of urban green infrastructure and landscape pattern:process relationship. Similarly to green infrastructure networks categorized as the system of hubs, links, and sites, urban green spaces can be analyzed as landscape structures through such concepts as the universally accepted mosaic model that defines three major landscape elements: patches, corridors and matrix (Table 3.2.2). Quintas and Curado (2010) claim that such an approach allows an assessment not only of the ecological character, but also of its social value.

Table 3.2.2 Examples of urban landscape elements classified in the patches-corridors-matrix model (Credits: Ahern, 2007)

Urban Patches	Urban Corridors	Urban Matrix
• Parks • Sportfields • Wetlands • Community gardens • Cemeteries • Campuses • Vacant lots	• Rivers • Canals • Drainageways • Riverways • Roads • Powerlines	• Residential neighborhoods • Industrial districts • Waste disposal areas • Commercial areas • Mixed use districts

Based on *Land Mosaics* by Richard Forman (1995), Ahern (2007) claims that urban patches provide multiple functions, particularly wildlife habitat, aquifer recharge areas, sources and sinks for species and nutrients. Urban corridors also serve such functions as habitat for wildlife, pathways or conduits for the movement of species, nutrients, or wind. Urban matrix is the dominant landscape structure in terms of area, level of connectivity, and control over the landscape and its dynamics (Ahern, 2007).

From the perspective of the landscape mosaic model urban green spaces are mainly represented by patches and corridors. As both of them cover multiple ecological functions their role in urban areas should not be neglected.

According to Quintas and Curado (2010), urban patches can be additionally divided into cores and edges. Their qualities and accessibility are essential for natural processes and social activities implementation (Table 3.2.3). In terms of social value the attractiveness is one of the major functions, which is directly interrelated with qualities and accessibility of a patch and its components. Quintas and Curado (2010) determine heterogeneity, diversity, typologies, dynamics of elements, and size of a patch core as indicators that can be assessed as qualities both at social and ecological levels. These indicators are particularly important in determining the general quality of a patch. Patch edges play a key role in accessibility of the core affecting the relationship between a patch and surroundings (Quintas & Curado, 2010). Corridors are the landscape structures that provide connectivity and coherence in the landscape making the flux of energy, materials, nutrients, and organisms possible. The ecological functions of stepping stones are identical to those of the corridors. At the social level the corridors may function as a connection basis for transport systems providing movement of people across the landscape (Quintas & Curado, 2010).

Table 3.2.3 Structure and functions of urban green infrastructure (Adapted from Quintas & Curado, 2010)

		STRUCTURE		
		Patch		Corridor
		Core	Edge	
FUNCTION	ECO	Qualities	Accessibility	Connectivity
	SOC	Attractiveness		

Essentially, the physical and functional connectivity concept is one of the key ideas from landscape ecology that is relevant to urban green infrastructure (Ahern, 2007). Connectivity illustrates the relationship between landscape structure and function. Reduced connectivity along with a high degree of fragmentation are typical for modified landscapes such as urban environments (Ahern, 2007).

Returning to complications in defining and categorizing green infrastructure caused by a variety of applied scales, there is another concept typical for applied landscape ecology and based on the theory of hierarchical systems. The multi-scaled approach addresses the structure and systems that function simultaneously at multiple scales (Ahern, 2007). In landscape ecology such an approach is the accepted norm, which addresses spatial patterns and ecological processes (Ndubisi, 2002). The analyses based on multi-scaled approach normally help indicate key points for physical linkages (Ahern, 2007).

A good example of a comprehensive and inclusive model consonant with the theoretical view on human impact on natural systems is the widely accepted in landscape planning Abiotic, Biotic and Cultural (ABC) resource model (Ahern, 1995; Ndubisi, 2002). The multifunctional suite of ecological and social functions that can be represented by the model supports the broad principles of sustainability. Ahern (2007) emphasizes the holistic ecosystem vision of urban environment by giving an illustrative example on how the ABC resource model can be applied to urban green infrastructure in order to underscore its key ecological functions (Table 3.2.4).

Table 3.2.4 Key abiotic, biotic and cultural functions of urban green infrastructure (Credits: Ahern, 2007)

Abiotic	Biotic	Cultural
● Surface:groundwater interactions ● Soil development process ● Maintenance of hydrological regime(s) ● Accomodation of disturbance regime(s) ● Buffering of nutrient cycling ● Sequestration of carbon (and greenhouse gasses) ● Modification and buffering of climatic extremes	● Habitat for generalist species ● Habitat for specialist species ● Species movement routes and corridors ● Maintenance of disturbance and successional regimes ● Biomass production ● Provision of genetic reserves ● Support of flora:fauna interactions	● Direct experience of natural ecosystems ● Physical recreation ● Experience and interpretation of cultural history ● Provide a sense of solitude and inspiration ● Opportunities for healthy social interactions ● Stimulus of artistic/abstract expression(s) ● Environmental education

It is not an easy task for planners and practitioners to design an urban landscape in a way that would provide a complete suite of ABC functions. Ahern (2007) provides an example of how differently ABC functions can perform in terms of the level of human intrusion into such ecosystems as river channels and streams (Figure 3.3).

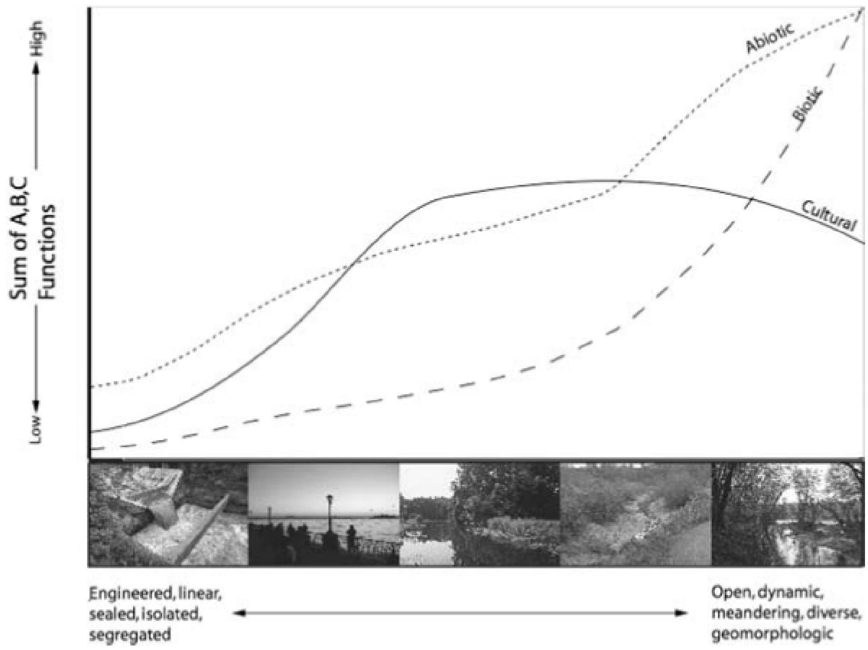


Figure 3.3 Abiotic, biotic, and cultural functions in a continuum of hydrological/stream types (Credits: Ahern, 2007)

It is evident that engineered streams and canals have significantly lower sum of ABC functions in comparison to naturally open and dynamic streams. However, as urban creek becomes more natural and meandring its cultural functions are decreasing, while abiotic and biotic functions increase.

Multiple functions and services of green infrastructure can be delivered by strategically planned and properly maintained urban green spaces, particularly in urban areas. The conditions and balanced presence of urban parks and gardens are responsible for the regulation of air quality, water, and local climate (MEA, 2005). The ABC resource model is, to a certain extent, consistent with the ecosystem services concept – the universally accepted list of benefits that people obtain from ecosystems. But unlike the functions of urban green infrastructure the ecosystem services are directly linked to human beneficiary. This is what by nature makes services and functions different (Chan et al., 2006). The following chapter reviews the links between urban green infrastructure, particularly green open spaces, and the concept of ecosystem services.

3.3 Ecosystem services and green infrastructure at the urban scale

As previously mentioned, green infrastructure on the local, or urban, scale encompasses different elements and areas such as street trees, public and private gardens, major recreational spaces, city forests and woodlands, and many others. These structures provide local inhabitants with physical, economic, intangible well-being, and other numerous benefits that are commonly referred to as *ecosystem services* (MEA, 2005; Austin, 2014; Pulighe et al., 2016). At first, it is important to emphasize that the ecosystem services concept is an anthropocentric view on natural systems that tends to interpret their value in cost-benefit terminology of economics. It is hoped that such an approach to illustrate the economic benefits of healthy ecosystems will lead to a greater public commitment and investments into conservation of natural systems (Austin, 2014).

One of the most comprehensive and seminal studies that aimed to develop a framework linking ecosystem services and human well-being through socio-economic factors - the Millennium Ecosystem Assessment (MEA) - defines ecosystem services simply as *'the benefits people obtain from ecosystems'* (MEA, 2005). The concept of ecosystem services has received much attention in terms of policy debates on ecological infrastructure and been addressed by other major initiatives as well - for instance, the Economics of Ecosystems and Biodiversity (TEEB, 2010).

The MEA (2005) and the TEEB (2010) conceptually frame and classify ecosystem services into four major categories: (a) *supporting (and habitat) services* (e.g. nutrient cycling etc.); (b) *regulating services* (e.g. climate and water regulation, pollination etc.); (c) *provisioning services* (e.g. food, water, fibre etc.); and (d) *cultural (and amenity) services* (e.g. recreation, education etc.) (Table 3.3.1). Considering such a categorization, the definition of ecosystem services can be amplified as *'the delivery, provision, protection or maintenance of goods and benefits that humans obtain from ecosystem functions'* (Tzoulas et al., 2007).

Table 3.3.1 Classification of ecosystem services based on the Millenium Ecosystem Assessment (MEA, 2005) and the Economics of Ecosystems and Biodiversity initiative (TEEB, 2010) (Adapted from Gómez-Baggethun et al., 2013)

Provisioning Services *Products obtained from ecosystems*	**Regulating Services** *Benefits obtained from regulation of ecosystem processes*	**Cultural & Amenity Services** *Nonmaterial benefits obtained from ecosystems*
- Food - Fresh water - Fuelwood - Fiber - Biochemicals - Genetic resources	- Climate regulation - Disease regulation - Water regulation - Water purification - Pollination	- Spiritual and religious - Recreation and ecotourism - Aesthetic - Inspirational - Educational - Sense of place - Cultural heritage
Supporting & Habitat Services *Services necessary for the production of all other ecosystem services*		
- Soil formation - Nutrient cycling - Primary production - Habitat for species - Maintenance genetic diversity		

The categorization of ecosystem services into these four classes is valuable and commonly referred to by researchers in multiple fields, but one may argue that it is not well connected to the *"three E's"* of sustainability (Economy, Environment and (social) Equity) mentioned before (Wheeler & Beatley, 2002). Such a classification also does not prioritize specifically urban ecosystem services, which are distinctive for human-dominated land cover types and urban green spaces and can be expected to be of major importance for urban populations (Chiesura, 2004; Jansson, 2014). The efficiency of urban ecosystem services depends pretty much on the qualities of urban green spaces (Jansson, 2014). Many researchers urge to emphasize the importance of adapting the ecosystem services classification to urban areas in terms of land use planning and management in association with urban green infrastructure (Bolund & Hunhammar, 1999; Gómez-Baggethun et al., 2013; Pulighe et al., 2016).

3.3.1 Links between green infrastructure, ecosystem services, and human health

The Mapping and Assessment of Ecosystems and their Services (MAES) is the initiative of the European Union's Biodiversity Strategy to 2020 that aims to develop ideas for a coherent framework to map and assess ecosystem services in Europe in order to maintain and enhance them in a sustainable way (Maes et al., 2018). The fifth MAES report presents a simplified model of the concept of ecosystem condition and its linkage to human well-being through ecosystem services (Figure 3.4). According to the Millennium Ecosystem Assessment the concept of ecosystem condition reflects the capacity of an ecosystem to deliver ecosystem services, relative to its potential capacity (MEA, 2005).

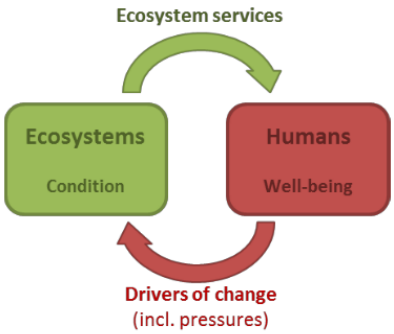


Figure 3.4 Simplified conceptual model for Mapping and Assessment of Ecosystems and their Services (MAES) initiative (Credits: Maes et al., 2018)

The MAES conceptual model implies that ecosystems need to be maintained in good condition in order to provide essential ecosystem services and deliver benefits, therefore impacting the well-being of humans. In turn, drivers of change by people can be divided as positive (e.g. conservation) and negative (e.g. pressures) impacts on ecosystem condition (Maes et al., 2018).

Green infrastructure as a biological component that constitutes cities can contribute to ecosystem condition and health in many different ways. For instance, green infrastructure is one of the key elements of urban ecosystems, developing which can serve for connecting natural core areas and, therefore, reducing fragmentation and enhancing ecosystem condition (Maes et al., 2018).

On the other hand, the ability of green infrastructure to deliver the services is dependent on the health and viability of the ecosystem (Austin, 2014). Therefore, in order to understand the interlinkages between green infrastructure and ecosystems it is important to fully perceive the concept of ecosystem health. Tzoulas et al. (2007) state that definitions of ecosystem health presented in modern literature are strongly tied up with the concepts of stress ecology. Thus, an ecosystem may be considered healthy if it is resistant to stress and degradation, while being able to maintain its organisation, productivity and autonomy.

In the conceptual framework that aims to integrate green infrastructure, ecosystem and human health (Figure 3.5), Tzoulas et al. (2007) include urban green infrastructure typology developed by the UK's Department for Transport, Local Government and the Regions in 2002, which, according to authors, is inclusive and flexible for application in different urban settings. With respect to the model of ecosystem health developed by Lu and Li (2003), authors suggest six parameters that indicate ecosystem health and are essential for ecosystem functioning. As mentioned previously, there are a number of ecosystem functions and services identified by multiple studies and research initiatives (Pickett et al., 2001; de Groot et al., 2002; MEA, 2005; TEEB, 2010). The conceptual framework by Tzoulas et al. (2007) selects eight ecosystem services and functions that are based on a framework developed by Pickett et al. (2001).

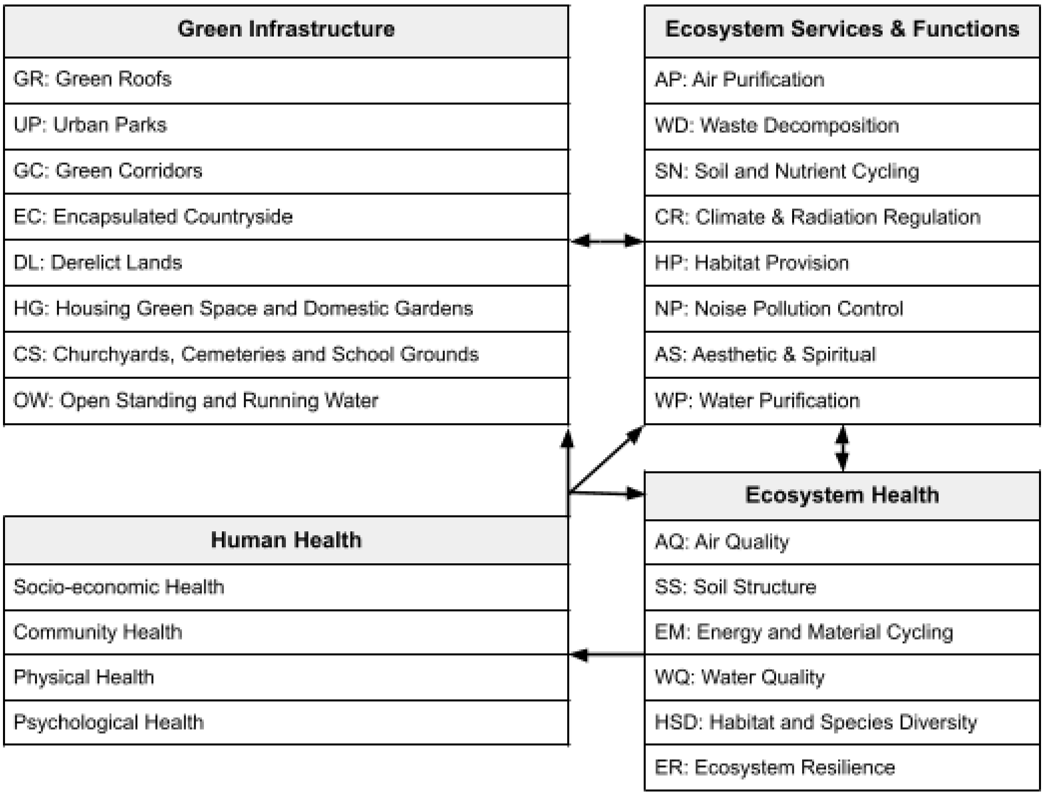


Figure 3.5 Conceptual framework of interrelations between green infrastructure, ecosystem and human health (Adapted from Tzoulas et al., 2007)

Ecosystem health is closely related to ecosystem services. For example, a greater ecological stress leads to a reduction of quality and quantity of ecosystem services, while ecosystems that are considered healthy have a greater capacity for a range of ecosystem services (Lu & Li, 2003; Tzoulas et al., 2007). Both ecosystem health and ecosystem services are linked with the green infrastructure too. Vegetation cover formed by green infrastructure contributes to the conservation of biodiversity, which is one of the most important indicators of ecosystem health that contributes to its resilience (Rapport, 1995; Niemelä, 1999a). Besides, as mentioned before, green infrastructure provides the basis for ecological networks, which, in its turn, reduces ecological impact of habitat fragmentation (Maes et al., 2018).

Green infrastructure also creates the environmental basis for public health through the state of its ecosystem services and functions (Tzoulas et al., 2007). Various studies exploring the contributions of green spaces and nature to human health has distinguished that, for instance, cultural ecosystem services often represented by intangible and non-material benefits directly contribute to human health particularly in urban areas (Maas et al., 2006; Toftager et al., 2011; Skärbäck et al., 2014).

It is also important to note that ecosystem management, especially in urban areas, is guided by human needs, socio-economic factors and cultural conditions. Hence, public health state can also be a factor for modifying environments what makes this relationship interdependent (Tzoulas et al., 2007). The two-ways interactions between ecosystem health, services and green infrastructure and human health are indicated in the model at Figure 3.5. This model is one of the illustrative ways to show the role of green infrastructure in the relationships between ecosystem and human health systems. Based on the analysis Tzoulas et al. (2007) state that *'ecosystem services provided by a green infrastructure can provide healthy environments and physical and psychological health benefits to people residing within them'*.

Evidently, there are other categories of benefits of urban green infrastructure that can be distinguished besides human health. Lately many studies have shown the multiple benefits that can be derived from urban green infrastructure and their ecosystem services (Chiesura, 2004; Benedict & McMahon, 2006; Austin, 2014; Pellegrino et al., 2014). For example, Jansson (2014) tries to cover the range of economic, social and ecological aspects of sustainability as well as the categories of ecosystem services from a perspective of a planning practice and divides the benefits of urban green spaces into four categories: economic, health, quality of life, and ecological.

There are many other examples of attempts to illustrate the benefits of incorporating green infrastructure into the planning practice underpinning the commonly recognized typology of ecosystem services. For instance, Landscape Institute (2009) provides the next list of benefits of green infrastructure: climate change adaptation, climate change mitigation, water management, dealing with waste, food production, biodiversity enhancement, recreation and health, economic values, local distinctiveness, education, and stronger communities.

Considering the above mentioned benefits of green infrastructure mentioned by various studies and their close linkage with ecosystem services and functions, it is reasonable to acknowledge the importance of ecosystem services concept in green infrastructure planning practices and its high level of acceptance within academia and practitioners. The concept of ecosystem services along with their typology designated by Millennium Ecosystem Assessment (MEA, 2005) became a common ground for the researchers in multiple fields of study. Nonetheless, as has been mentioned before, urban studies are lacking the general typology of ecosystem services peculiar to urbanized areas. The attempts to identify and distinguish urban ecosystem services and their relation to urban green spaces are discussed in the following section.

3.3.2 Urban ecosystem services

One of the first researchers who attempted examining the theoretical background of urban ecology and tried to assess the characteristics of urban ecosystems was Jari Niemelä (Niemelä, 1999a, 1999b). Considering the variety of definitions for both *'ecology'* and *'urban'*, his study has indicated that the discipline of urban ecology can be generally defined as ecological research in the urban setting. He also highlights that urban ecology is by nature an applied science, since urban ecological studies are usually aimed to be applied in planning and management of urban green areas (Niemelä, 1999a).

As mentioned above, the term *'ecology'* can be considered and referred to from various perspectives. In the *Humanity and Nature: Ecology, Science and Society* Haila and Levins (1992) state that the concept of ecology exists in several different dimensions. *'Ecology the science'* is the biological discipline that emphasizes investigating the economy of nature, particularly flows of matter and energy as well as distribution and abundance of organisms (Haila & Levins, 1992; Niemelä, 1999a). Another way of considering ecology is as a resource base for humans and material basis for human existence. In this case the term *'ecology'* is usually seen as a *nature* (*'Ecology the nature'* as described by Haila and Levins). Such a vision is in line with the concept of ecosystem services supported by various scientists (Pickett et al., 2001; de Groot et al., 2002; Tzoulas et al., 2007; Austin, 2014; Jansson, 2014; Pulighe et al., 2016) and multiple research initiatives (MEA, 2005; TEEB, 2010; Maes et al., 2018).

Some of the first attempts to identify and classify the ecosystem services peculiar precisely to urban areas were attained in 1999 by Bolund and Hunhammar. Authors considered urban ecosystems simply as all natural green and blue areas in the city, including street trees and ponds. This way they distinguished seven different urban ecosystems such as street trees, lawns/parks, urban forests, cultivated lands, wetlands, lakes/sea, and streams (Bolund & Hunhammar, 1999).

Urban ecosystem services described by Bolund and Hunhammar (1999) (Table 3.3.2) are based on the general typology of ecosystem services determined by Costanza et al. in 1997, who identified 17 major categories of services. Based on the research of urban ecosystem services in Stockholm, Bolund and Hunhammar (1999) discovered that such categories as micro-climate regulation and recreational/cultural values are the only services provided by all the identified urban ecosystems. In its turn, wetlands were shown as the most valuable ecosystem type since it contributes to all services including sewage treatment (Bolund & Hunhammar, 1999) (Table 3.3.2). Previously, Costanza et al. (1997) had come up with the same correspondence and ranked wetlands as the most valuable terrestrial type of ecosystem per hectare.

Unlike the study of Bolund and Hunhammar (1999), who based their classification of urban ecosystem services on the typology of ecosystem services distinguished by Costanza et al. (1997), the subsequent attempts to identify and classify urban ecosystem services were predominantly based on the typology proposed by the MEA (2005).

Eventually one of the most comprehensive attempts to describe and classify urban ecosystem services was made by Gómez-Baggethun et al. (2013). This study, as well as the one by Bolund and Hunhammar in 1999, goes beyond the perception of urban ecology as *a science* ('the ecology *in* cities') and emphasizes 'the ecology *of* cities', which goes along with the vision of urban ecology as *a nature*, to put it in the words of Niemelä (1999a). Such a perception is represented by multiscale and interdisciplinary studies that emphasize social-ecological systems approach (Pickett et al., 2001; de Groot et al., 2002; Tzoulas et al., 2007) and, according to Niemelä

(1999a) and Haila and Levins (1992), consider ecology as a resource base for humans.

Table 3.3.2 Urban ecosystem services described by Bolund and Hunhammar (1999) and urban ecosystems providing the services

Ecosystem services	Urban ecosystem types
Air filtering (gas regulation)	Street trees, lawns/parks, urban forests, cultivated lands, wetlands
Micro climate regulation	Street trees, lawns/parks, urban forests, cultivated lands, wetlands, streams, lakes/sea
Noise reduction (disturbance regulation)	Street trees, lawns/parks, urban forests, cultivated lands, wetlands
Rainwater drainage (water regulation)	Lawns/parks, urban forests, cultivated lands, wetlands
Sewage treatment (waste treatment)	Wetlands
Recreation/cultural values	Street trees, lawns/parks, urban forests, cultivated lands, wetlands, streams, lakes/sea

In the study by Gómez-Baggethun et al. (2013) authors use the concept of ecological infrastructure that emphasizes the role of water and vegetation in delivering ecosystem services. Authors state that ecological infrastructure includes all 'green and blue spaces' in urban and peri-urban areas referring to the typology of green infrastructure assets used by the EEA (2011) and Landscape Institute (2009). However, the study does not pay particular attention to urban ecosystem components and their classification, but rather focus on urban ecosystem services provided by ecological infrastructure in general.

The classification of important urban ecosystem services suggested by Gómez-Baggethun et al. (2013) is based on the classification frameworks by the MEA (2005) and the TEEB (2010) initiatives, but also refers to the study by Bolund and Hunhammar (1999). The classification includes 15 urban ecosystem services categorized under four groups in accordance with the MEA (2005) typology (see Table 3.3.3).

Besides urban ecosystem services, both studies mentioned above also touch on negative aspects of urban ecosystems for human well-being, or ecosystem disservices (Bolund & Hunhammar, 1999; Gómez-Baggethun et al., 2013). Gómez-Baggethun et al. (2013) provides the next list of 7 ecosystem disservices: (a) air quality problems (e.g. volatile organic compounds); (b) view blockage; (c) allergies; (d) accidents (e.g. due to break up of branches and trees); (e) fear and stress (e.g. in dark green areas in night-time); (f) damages to infrastructure; (g) habitat competition with humans (e.g. some insects perceived as scary, unpleasant).

Nevertheless, it is clear that urban ecosystem services primarily contribute to enhancing resilience and quality of urban life. The research by Gómez-Baggethun et al. (2013) outlines that ecosystem services that can be especially relevant for urban areas involve noise reduction, urban temperature regulation, moderation of climate extremes, outdoor recreation, cognitive development, and social cohesion.

Table 3.3.3 Classification of urban ecosystem services and examples of their provision through ecological infrastructure components (Adapted from Gómez-Baggethun et al., 2013)

Group	Ecosystem service	Example
PS	**Food supply**	Vegetables produced by **urban allotments** and **peri-urban areas**
	Water supply	**Vegetation cover and forests** in the city catchment influence the quantity of available water
RS	**Urban temperature regulation**	**Trees and other urban vegetation** provide shade, create humidity and block wind
	Noise reduction	Absorption of sound waves by **vegetation barriers**
	Air purification	Absorption of pollutants by **urban vegetation** in leaves, stems and roots
	Moderation of climate extremes	Storm, flood, and wave buffering by **vegetation barriers**; heat absorption during severe heat waves; intact **wetland areas** buffer river flooding
	Runoff mitigation	**Soil and vegetation** percolate water during heavy and/or prolonged precipitation events
	Waste treatment	Effluent filtering and nutrient fixation by **urban wetlands**
	Pollination, pest regulation and seed dispersal	**Urban ecosystem** provides habitat for birds, insects, and pollinators
	Global climate regulation	Carbon sequestration and storage by the biomass of **urban shrubs and trees**
CS	**Recreation**	**Urban green areas** provide opportunities for recreation, meditation, and relaxation
	Aesthetic benefits	**Urban parks** in sight from houses
	Cognitive development	**Allotment gardening** as preservation of socio-ecological knowledge
	Place values and social cohesion	**Urban green spaces** provide opportunities for interaction between individuals and groups, hence promote social cohesion and reduce criminality
HS	**Habitat for biodiversity**	**Urban green spaces** provide habitat for birds and other animals

Note: PS - Provisioning Services, RS - Regulating Services, CS - Cultural Services, HS - Habitat Services

The more recent research that aims to quantify mapping approaches of urban ecosystem services and based on seven international seminal studies also has indicated multiple ecosystem services that are relevant in specifically urban context (Pulighe et al., 2016). Authors underscore the relevance of such urban ecosystem services as food production, educational services, greenhouse gas reduction, carbon storage, soil quality, cooling effect, and supporting biodiversity (Pulighe et al., 2016).

Both works, of Gómez-Baggethun et al. (2013) and Pulighe et al. (2016), emphasize the importance of integration of various fields of knowledge into interdisciplinary field combining the skills of researchers with different backgrounds. For instance, Gómez-Baggethun et al. (2013) distinguish a range of values of ecosystem services, including biophysical, economic, socio-cultural, health, environmental justice, and insurance values. According to Pulighe et al. (2016), connecting environmental, social, and biophysical methods with geographic perspective makes it possible to integrate the ecosystem services into a spatial dimension in order to map the ecosystem services and improve urban planning methods.

Apart from Gómez-Baggethun et al. (2013), other researches also highlight the exceptionally high role of cultural ecosystem services in urban context whether it regards recreation, cognitive development, aesthetic benefits, or social cohesion (de Groot et al., 2002; Chiesura, 2004; Maas et al., 2008). The health benefits and improved quality of life due to presence of urban green areas also have been a relevant topic for the research in multiple fields (Figure 3.5) (Maas et al., 2006; Tzoulas et al., 2007; Jansson, 2014).

Over the last two decades a number of studies in public health and urban planning fields have highlighted the importance of urban green spaces not only for recreation and aesthetics, but also for general physical activity of population, particularly walking and bicycling (Saelens et al., 2003; Toftager et al., 2011; Stefánsdóttir, 2014; Mäki-Opas et al., 2016). The following chapter reviews current findings from the studies that attempted to link presence and amount of urban green spaces with cultural ecosystem services, particularly those influencing physical activity of population through walking and cycling, thus benefiting the public health state.

3.4 Urban green spaces and physical activity

The Common International Classification of Ecosystem Services (CICES) regards cultural ecosystem services as the *'environmental settings, locations, or situations that give rise to changes in the physical or mental states of people, and whose character are fundamentally dependent on living processes'* (Haines-Young & Potschin, 2013). The classification also distincts those settings that support human-nature interactions and used for physical activities such as hiking, angling or bicycling, and those used for intellectual, analytical or mental activities that involve, for instance, intellectual and representational interactions. The report also recognizes spiritual, emblematic and other interactions that involve cultural outputs as cultural ecosystem services (Haines-Young & Potschin, 2013).

According to Wahlgren (2011), the research on the relation between physical activity and environments appear from mainly three fields of study: (a) health, including public health, exercise and behavioral sciences (Saelens et al., 2003; Maas et al., 2008); (b) urban planning, including travel behaviour, transport planning, urban design and geography (Winters et al., 2010, 2011; Stefánsdóttir, 2014); (c) parks, recreation and leisure sciences (Kaczynski & Henderson, 2007).

According to the World Health Organisation, urban green spaces are a fundamental component of any urban ecosystem that plays a critical role in facilitating physical activity, development of safe routes for walking and bicycling, along with multiple ecological benefits (WHO, 2016). A range of studies have reported the empirical evidence over the connection between the distance to urban green spaces and physical activity of population (Saelens et al., 2003; Kaczynski & Henderson, 2007; Toftager et al., 2011).

Based on the literature review of 50 studies that analysed a relationship between urban parks and physical activity, Kaczynski and Henderson (2007) found that 80% of them either reported positive relationships or had mixed findings that included at least some positive association. Interestingly, the authors noticed a stronger linkage between physical activities and such spaces as parks, trails, natural settings, open spaces, and golf courses rather than recreation centers, exercise facilities, and sport facilities (Kaczynski & Henderson, 2007).

Many behavioral medicine studies and articles also acknowledge a substantially strong association between neighborhood environment characteristics and walking or cycling. Based on the findings from transportation literature, Saelens et al. (2003) distinguish higher density, greater connectivity, and more land use mix as the main environmental factors influencing probability of walking and cycling for transport. Besides, among other factors affecting the choice to walk or cycle for either transport or recreation purposes authors name safety (e.g. traffic), infrastructure conditions (walking trails, bike lanes, sidewalks, etc.), presence of parks and physical activity facilities, and general neighborhood aesthetics and topography (Saelens et al., 2003).

The study of stimulated aesthetic experience by commuting bicyclists conducted in Iceland and Norway showed that environments like *'urban greenery'* and *'natural space'* were considered by cyclists as most attractive (Stefánsdóttir, 2014). The possibility to move continuously was also regarded as very important. According to the research, visual features that stimulate aesthetic experience by cyclists include vegetation, historical sights, clearly defined streetscapes and seeing other people at some distance. The author suggests that instrumental improvements along bicycle routes would improve not only instrumental experiencing of urban space, but also aesthetic one (Stefánsdóttir, 2014).

Nevertheless, not all the studies have found a strong relation between physical activity and urban green space. The Dutch study by Maas et al. (2008) has shown that the amount of green space in the living neighborhood is scarcely related to the level of physical activity for commuting purposes among the residents. Authors suggest that the reason behind that is the decreased facility density and increased possibility to park a car in the greener living environments (Maas et al., 2008). However, the study conducted earlier has recorded a positive association between percentage of green space in the neighborhood and self-perceived general health of its residents (Maas et al., 2006). Likewise, the results of Danish study based on cross-sectional surveys has shown an association between self-reported physical activity and distance to green space (Toftager et al., 2011).

The negative contribution of green space to commuting physical activity has been also identified by the research project carried out among the working population in Finland (Mäki-Opas et al., 2016). Similarly to Maas et al. (2008), authors explain it by unsuitability of green areas outside urban cores for commuting physical activity and general leaning of residents towards cars or public transport due to longer distances (Mäki-Opas et al., 2016). This is the case, when the access to green areas, better connectivity and higher density of facilities (Saelens et al., 2003) affect the choice of residents over preferred type of mobility. Based on the findings, the study by Mäki-Opas et al. (2016) also suggests that a good infrastructure as well as a high proportion of cycling and pedestrian networks and a good access to green spaces contribute positively to walking and cycling for commuting purposes.

Based on multiple sources, Wahlgren (2011) also suggests that infrastructure is one of the main factors of the route environment related to bicycling. In fact, the author distinguishes four factors: (a) bicycle-related infrastructure; (b) safety; (c) road users; (d) the ‘natural’ environment and aesthetics. Evidently, the requirements to the route environment might differ with the respect to the type and purpose of physical activity. Cycling purposes are commonly divided into those for: (a) transport (commuting); (b) recreation; (c) exercise (including competition) (Wahlgren, 2011).

According to the study by Winters et al. (2010), the characteristics of the route are more prominent than origin and destination characteristics in terms of cycling for commuting purposes. Thus, when studying the impact of urban green spaces on bicycling for transport, it is perhaps more important to consider route qualities rather than only distance to green spaces from the origin or destination locations like it was undertaken in the studies by, for instance, Maas et al. (2008) and Mäki-Opas et al. (2016). However, Winters et al. (2010) underscore the necessity of considering all spatial zones for comprehensive bicycling research.

Similarly to the factors indicated by Wahlgren (2011), the survey of motivators and deterrents of cycling in Vancouver pointed out four top factors for making a trip by bicycle and they all are predominantly related to the route environment: (a) being away from traffic and noise pollution; (b) having beautiful scenery; (c) having separated bicycle lanes for the entire distance; (d) having flat topography (Winters et al., 2011). Apart from these factors, traffic calming, higher route connectivity and intersection density, local roads instead of highways are also considered as the features that increase a likelihood of cycling (Winters et al., 2010). For the bicycle infrastructure planning agencies Winters et al. (2011) suggest key considerations that include: (a) the potential of physical separation of bicycles from motor vehicles; (b) minimizing slopes; (c) travelling through aesthetically pleasing locations; (d) serve popular destinations, including transit lines.

An adaptive stated preference study of cycling facilities by Tilahun et al. (2007) has shown that users are willing to use more time-consuming routes for designated bike lanes, absence of parking in the street, and off-road bike lanes. The recruited individuals were ready to travel up to twenty minutes longer in order to avoid unmarked on-road bike lanes with side parking in favour of using an off-road bicycle trail (Tilahun et al., 2007).

Multiple studies including those mentioned above have highlighted the importance of bicycle infrastructure for increasing bicycling rates. To sum up, among the commonly referred factors related to bicycling infrastructure are: (a) presence of off-road bicycle paths; (b) minimized amount of parked cars and car parking facilities; (c) possibility of continuent movement with less interruptions; (d) surface quality maintenance (Wahlgren, 2011). Perhaps, the concerns of cyclists over infrastructure are predominantly related to safety issues, particularly connected with the presence of motor traffic (Wahlgren, 2011).

As previously mentioned, green infrastructure and aesthetics have somewhat contradictory relation to willingness of bicycling among the population. However, a number of studies, including those above mentioned, record a positive association between bicycling and the presence of greenery, hilliness and general aesthetics (Kaczynski & Henderson, 2007; Saelens, 2003; Stefánsdóttir, 2014; Tilahun et al., 2007; Wahlgren, 2011; Winters et al. 2010, 2011). Urban green infrastructure, particularly green open spaces as indicated by Bartesaghi Koc et al. (2017), seem to provide a room for creating and improving safe bicycle-related infrastructure for both recreational and transport bicycling. Policy making in urban planning, particularly related to transportation, that considers these possibilities appropriately might be able to increase general willingness among the population to use bicycles for various reasons more often.

Evidently, there are multiple factors influencing bicycling in various ways. The presence, amount and proximity to urban green spaces is only one of them. The findings that prove this association are related to different fields of study and based on a variety of different research strategies from cross-sectional public surveys to GIS based mapping. However, all of them can be also critically questioned.

Most studies of bikeability as well as walkability seem to derive from North America (predominantly US and Canada), Australia, and Northern Europe (particularly Sweden, Finland, and Denmark) and the Netherlands. There is an evident scarcity of research on the relation between bicycling and green open spaces in Prague and other Central European urbanized areas. Nevertheless, the green infrastructure concept along with ecosystem services it delivers seem to gain much attention among scientists and practitioners across the globe, hence the scientific basis for its use for the instrumental improvements of cycling conditions is present.

4. Methodology

The present study covers the whole territory of the city of Prague and is based on the evaluation of two of its systems: network of cycle routes and urban green spaces. The methodology and sequence of the analysis are described in the chapter below, but first of all the data sources and technical details of the research are presented.

A major part of the research is made using the geographic information system (GIS). The software used for data processing is the QGIS version 3.10.12. Geographic data were acquired from the open data of the Geoportal managed by the Prague City Hall and Prague Institute of Planning and Development (IPR Praha) (Table 4.1.1) (Geoportal, 2021). The coordinate reference system (CRS) used in the datasets is EPSG:5514 - S-JTSK / Krovak East North. The same CRS has been used by the author in the course of the whole research section.

Table 4.1.1 GIS datasets used in the research

Dataset Identifier	Type of data	Last Update	Indicates	Description
CZ-70883858-DOP_CUR.DOP_Cyklotrasy_l	Polyline shapefile	30.11.2020	System of Prague cycling routes	Data include the numeration of Prague bikeways, their transport conditions and the state of realisation of their markings. The dataset is used by the author for cycle network analysis, and for extraction of network's sections commonly used by cyclists.
CZ-70883858-URK_CUR.URK_SS_VyuzitiZakl_p	Polygon shapefile	30.09.2020	Current land use map of Prague	Dataset presents the current distribution of various land use types across the city and contains information over accessibility of its segments. It is used by the author for extraction of green infrastructure elements along with full information about their current use and accessibility. Also, based on extracted vector data the rasters indicating their distribution were created.
CZ-70883858-D3M_CUR.DSM_1M	GeoTIFF raster	16.07.2020	Digital terrain model of Prague (DTM)	DTM encompasses data on elevations across Prague with 1 m resolution and is used by the author to calculate and present information about Prague's terrain, e.g. distribution of steep slopes.
CZ-70883858-ORT_CUR.ORT	GeoTIFF raster	16.12.2020	Orthophoto map of Prague	The aerial image of Prague with 10 cm resolution. It is used by the author for navigation and visual representation in generated maps.

Apart from the GIS datasets developed by IPR, other sources of information were used as well. Those include the heatmaps such as Strava Global Heatmap and the one based on the GPS records made by participants of the Bike to Work annual campaign and maintained by the Auto*Mat NGO in cooperation with other initiatives. Besides, the assessment of cycling intensity on the street-level is based on the analysis presented by the Umotional Analytics and also encompasses the data from bike counters installed across the city. More detailed information on all of the above-mentioned data sources and the ways data have been used by the author is presented in the following chapter.

4.1 Evaluation of cycling conditions in Prague

Designated bikeway system of Prague is a network of cycle routes that covers the entire area of the city. The system consists of over 1300 km of cycle routes labeled in a range from A1 to A499, although the majority of them are not yet marked or anyhow indicated in the streetscape. The system does not always suggest the shortest route but it aims to provide a bikeway involving quieter streets and safer environments. The main routes of the network are numbered as A1 and A2 and they follow the waterfronts of the Vltava river along both its banks. These routes are connected to the so-called secondary routes (A11-A27) that are often led by the Vltava streams or green spaces away from the city center.

The analysis of the bikeway system aims to show the share of segregated paths in the cycling infrastructure and compare it to the share of cycle routes that are either not separated from motor traffic or separated only as bike lanes.

According to the level of segregation of a cycle route from motor traffic, the author categorizes bikeways under two groups: (a) in-roadway bikeways, and (b) non-motorized traffic paths. In-roadway bikeways include three categories:

- **Not separated cycle routes** are the bikeways that have no physical infrastructure that would segregate a bicyclist or other non-motorized user from vehicles in the road. This category also includes the on-road bikeways that have some shared lane markings (‘sharrows’), mixed bus/cycle lanes, and bike contraflow lanes.
- **Bike lanes** are marked with paint on-road lanes devoted to cyclists. Lanes might be separated by painted buffers, but they have no physical separation from motorized traffic (Figure 4.1).
- **Traffic-calmed streets** are quiet roadways in non-urban areas or vehicles restricted zones that are part of the bikeway system.

The non-motorized traffic paths are also divided into three categories in accordance with the level of separation of bicyclists from other users:

- **Mixed-use paths** are paths dedicated to multiple non-motorized modes of transport with neither physical separation nor marked lanes for cyclists.
- **Bike paths** are exclusively segregated bike paths that often go along with mixed-used paths and trails (Figure 4.1).
- **Dismount from a bike required** are those segments of the bikeway system of Prague that require cyclists to dismount from a bicycle due to narrowness of the path (e.g. narrow sidewalk). The category also encompasses the ferry rides across Vltava.

Each type of designated cycle route that has fallen under some category in terms of its physical separation is indicated in Table 4.1.2. In order to evaluate the share of segregated segments of cycling infrastructure the length of selected categories is calculated by the 'vector statistics' tool in QGIS and compared to the total length of all bikeways in Prague. The results of count will be presented in the table and chart views.

Table 4.1.2 Categories of cycling infrastructure as regards transport conditions

Bikeway categories	Metadata codes for transport conditions used in the GIS dataset	English adaptation for transport conditions
Not separated cycle routes	**1** - Piktokoridor **3** - Buspruh **4** - Cykloobousměrka **9** - Přejezd přes silnici, křižovatku **11** - Obytná zóna **12** - Cyklotrasa v běžné ulici **13** - Průjezd zákazem vjezdu-legální **14** - Cyklojednosměrka **16** - Cyklotrasa na rušné komunikaci	Shared lane markings ('sharrows') Shared bus/cycle lane Bike contraflow lane Road crossing Residential area Bikeway in regular street Legalized thoroughfare for cyclists Bike one-way street Bikeway in busy street
Bike lanes	**2** - Cyklopruh **21** - Ochranný cyklopruh	Bike lane Buffered bike lane
Traffic-calmed roadways	**121** - Cyklotrasa ve zklidněné ulici **122** - Cyklotrasa v extravilánu **123** - Cyklotrasa na neprůjezdné silnici	Bikeway in traffic-calmed street Bikeway in non-urban area Bikeway in vehicle restricted street
Mixed-use paths	**5** - Bezmotorová cesta **6** - Stezka pro chodce a cyklisty společná **10** - Pěší zóna s cyklistickou dopravou **17** - MTB trasa, singletrack **18** - Chodník s povolením jízdy **20** - Chodník	Car-free roadway Mixed-use path for pedestrians and cyclists Pedestrian zone with bike traffic allowed MTB trail, singletrack Sidewalk with cycling permitted Sidewalk
Exclusive bike paths	**7** - Stezka pro chodce a cyklisty prostorově oddělená **8** - Samostatná cyklostezka	Spatially separated mixed-use path Segregated bike path
Dismount from a bike / Ferry	**15** - Cyklisto veď kolo **19** - Přívoz	Cyclists dismount Ferry

Spatial distribution of commonly taken routes can help indicate the gaps and inefficiencies in the current bikeway system and its relevance for local cyclists. The categorization of preferred routes may show what kind of cycling infrastructure and environment most of the cyclists happen to ride through. There are few sources that can be used for determining and mapping the bike routes often taken by cyclists. GPS records collected by users of various mobile applications are often used in data visualization and, thus, transportation research and urban planning.

Figure 4.1 Bike lane along Vinohradská street (on left) and bike path passing under Kukulova street (on right) (Source: 'Městem na kole' map)

A common way to depict collected GPS tracks over the maps is represented by heatmaps. The examples of those that may be used for analysis of cycling activity in Prague are Strava global heatmap, which is based on the records from Strava mobile application common among athletes, and the heatmaps of the GPS tracks collected by the participants of 'Bike to Work' (*'Do práce na kole'*) cycling campaign that involves approximately 5000 users in Prague (in 2019 and 2020) who record their bike rides to work during May each year (Figure 4.2) (Auto*Mat NGO, 2020).

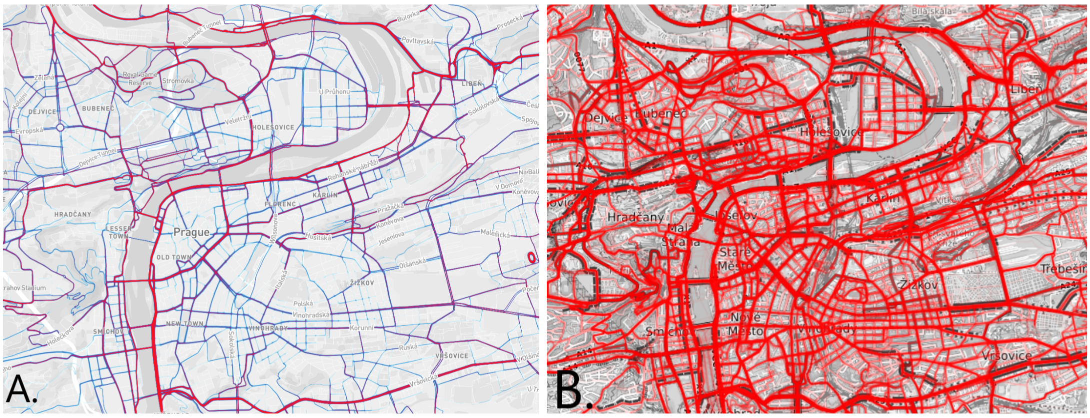


Figure 4.2 Heatmaps illustrating cycling intensity in Prague city center: (A) Strava global heatmap, and (B) 'Bike to Work' annual campaign 2020

Heatmaps are helpful in visualization of actual distribution of popular cycle routes. Nonetheless, in order to calculate and map frequently used cycle routes and compare them to the city bikeway system the author needs accurate data that would indicate the average number of rides through specific segments per day.

The identification of frequently used bikeways is based on the street-level cycling intensity analysis performed by Umotional Mobility Analytics, which is a company based in Prague and specialized in implementation of artificial intelligent solutions for transport and mobility. The analysis included mapping millions of kilometers of GPS tracks recorded by the users of application *'Na kole Prahou'* ('Prague by Bike') and counting data extrapolation from stationary bike counters across the city. The result of analysis is available online in a form of interactive visualization (Figure 4.3) (Umotional, 2019).

Figure 4.3 Visualization of street-level cycling intensity analysis in Prague by Umotional Analytics (Credits: Umotional, 2019)

Frequently used cycle routes were identified and categorized in accordance with the Umotional analytics research project, but some attention has been given by the author to the heatmaps of 'Bike to Work' and Strava. The most recent data presented by Umotional at the moment of this assessment is 2019. Bikeways selected for the research are divided by the author under two categories with respect to the estimated daily average number of bike rides within a particular segment of street or path during a cycling season (April to October):

- **Primarily used routes** are those with at least 100 riders passing in one direction on a daily average.
- **Secondarily used routes** are those with at least 50 riders passing in one direction on a daily average.

Primary and secondary routes that correspond to the designated bikeways according to the official network of cycle routes were manually selected in the IPR dataset and extracted to separate GIS files. Additionally, those segments of frequently used bikeways that are not related to any part of the designated cycle network were manually drawn and added to the map. Thus, the share of popular routes that are not considered by the bikeway system can be calculated. Additionally, the length of both categories of popular routes is counted, so the share of intensively used bikeways within the whole network can be evaluated.

In order to assess the share of segregated bike infrastructure in distribution of frequently used bikeways the classification that had been used in evaluation of the Prague bikeway system (Table 4.1.2) is also applied to the selected primary and secondary routes. This makes it possible to count the shares of in-roadway bikeways and non-motorized traffic paths in terms of distribution of frequently used cycle routes. The results are also presented in the table and chart views.

Stationary bike counters are another source of information that can help gain accurate data of intensity of cycling in particular locations. At the moment of research there were 30 stationary bike counters installed at the major cycle routes in Prague. The cameras are lodged by the Camea company specialized in intelligent transportation systems and traffic monitoring (Camea, 2021). The data and its historical overview gathered by camera traps are publicly available online through the Golemio data platform managed by the municipal company Operátor ICT specialized particularly in the Smart City projects (Figure 4.4) (Golemio, 2020).

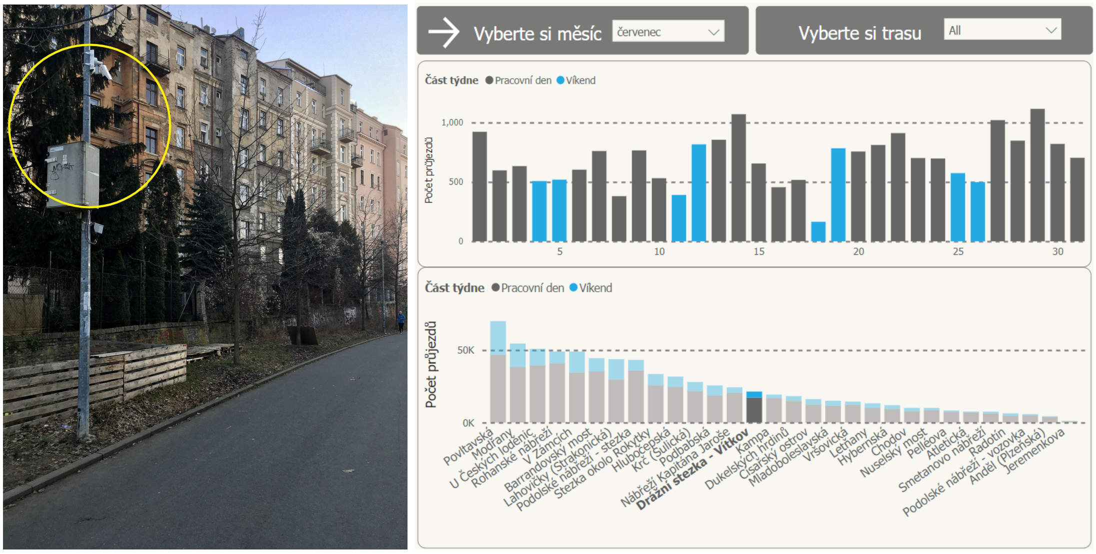


Figure 4.4 Example of bike counter at the cycle path alongside Vítkov hill (routes A25 and A257) and the data collected by it in June 2020 at Golemio data platform (Photo credits: author)

Although bike counters have been used for monitoring cycling intensity on main Prague bikeways since 2009, the Golemio data platform is a relatively new project (2019-2020) that still has some limits in functionality and defects in its scripts that lead to occasional occurrence of failures and outages in the data collection (Filler, 2020). For this work the author has used the data gathered in the period from April to September 2020 when a relatively low number of outages has occurred.

The data manually extracted from 19 steadiest bike counters represent the total number of detected rides each month and are separated on weekdays and weekends. In order to identify the average distribution of rides with respect to time of a week the author divides the numbers of rides detected by a particular bike counter on weekdays or weekends during the season 2020 on the total number of weekdays or weekend days during that period. This way the data help calculate the share of weekdays and weekend days in a daily average number of rides, which indicate the segments of the network that are more often used supposedly in recreation cycling and those that are rather taken on weekdays for ‘utility’ rides. The table indicating the results of calculations of data and the so-called weekdays:weekend ratio at locations where the bike counters are installed is presented.

Those days when failures or outages have occurred in the survey by bike counters have been excluded from the calculations. The counts done by the author are presented in the table view in Appendix 2 and are added to the GIS file as a separate vector layer along with other above-mentioned datasets.

Thus, analysis of Prague bicycling conditions and intensity of use of bike infrastructure involves three steps:

- The system of bikeways is categorized on the basis of physical separation from other modes of transport. The lengths and shares of selected categories are counted.
- Frequently used cycle routes are identified and categorized on the basis of street-level cycling intensity analysis. Primarily and secondarily used bikeways are mapped, their lengths and shares are calculated according to transport conditions. Different types of frequently used routes in terms of their physical separation are calculated and mapped as well. Besides, the shares of cycle routes that coincide with the system of designated bikeways are counted.
- The daily average number of rides detected in 19 major cycling locations is calculated on the grounds of data collected by bike counters during cycling season 2020. The shares of weekdays and weekends rides are counted for each location in order to specify which cycle routes are more used for commuting purposes and which for recreation.

4.2 Assessment of Prague urban green spaces and their qualities

An assessment of Prague green infrastructure is conducted at the city and local scales. Different types of urban green spaces are reviewed with respect to classification of green infrastructure assets developed by the Landscape Institute (2009) (Table 3.1.3) and being considered preponderantly as green open spaces as expounded by Bartesaghi Koc et al. (2017) (Table 3.1.4; Figure 3.2).

The classification of land use elements used in the GIS dataset created by the Institute of Planning and Development (IPR) has become a ground for determining categories of green infrastructure. Urban green spaces have included 25 types of land use and are grouped by the author under 4 large categories:

- Forest parks;
- Thickets and road verges;
- Recreational spaces and municipal parks;
- Gardens and grasslands.

Besides, in order to resemble the used classification with the one suggested by the Landscape Institute (2009) and other studies, apart from forests, parks, recreational areas, gardens and other green spaces, the study also covers other elements of green infrastructure such as pedestrian zones and plazas, agricultural lands, brownfields, and water objects (Table 4.2.1).

Figure 4.5 Examples of Prague green spaces and their categorization:
A - trail in Malešický forest (LRR);
B - path through the allotment gardens near Palmovka (RAZ);
C - walkway in the district park in Malešice neighborhood (RPP);
D - walkways in the park in Strašnice neighborhood (RPU) (Credits: author)

To calculate the areas and shares of each category of green infrastructure separate vector layers have been extracted from the IPR land use data. The tables and charts indicating calculated areas of various green infrastructure assets and shares of different green spaces are presented. Distribution of green infrastructure across the city area is represented by a raster map of Prague with 1x1 m resolution, created on the basis of extracted vector layers. The map also indicates the distribution of marked cycle routes within the network of designated bikeways to illustrate the general level of correspondence of these two systems.

Table 4.2.1 Classification of green infrastructure elements used in the research

Green infrastructure category	Land use codes	English adaptation	
Forest parks	**LRO** - lesy **LRR** - lesoparky	Forests Forest parks	Urban Green Spaces
Thickets and road verges	**ND** - doprovodná vegetace **NM** - mokřadní porosty bez dřevin **NNK** - nelesní porosty dřevin nezapojené s keři **NNO** - nelesní porosty dřevin nezapojené se stromy a keři **NNS** - nelesní porosty dřevin nezapojené se stromy **NZK** - nelesní porosty dřevin zapojené s keři **NZO** - nelesní porosty dřevin zapojené se stromy a keři **NZS** - nelesní porosty dřevin zapojené se stromy	*Road verges and various boscages and thickets encompassing different types of greenery such as small trees, shrubs, and wetland vegetation.*	
Recreational spaces and parks	**RAG** - golfová hřiště **RAP** - rekreační areály přírodní **RAZ** - rekreační a zahrádkové osady **RPH** - hřbitovy **RPP** - parky **RPU** - parkově upravené plochy **RV** - rekreační areály vzdělávací (ZOO, botanické zahrady)	Golf courts Natural recreation areas Recreational and allotment gardens Graveyards Parks Parklike spaces Educational recreation areas (ZOO, botanical gardens)	
Gardens and grasslands	**ZA** - zahradnictví **ZHB** - zahrady rodinných domů **ZHV** - zahrady a hřiště občanské vybavenosti **ZL** - louky, pastviny, travnatá lada **ZSO** - sady opuštěné **ZSP** - sady produkční **ZSV** - vinice **ZSZ** - zahrady	Gardening areas Family houses' backyards Playgrounds and gardens as public facilities Meadows, grasslands, grazing lands Disused gardens Yielding gardens Vineyards Garden yards	
Pedestrian zones	**VC** - cesty **VPP** - pěší prostranství **VPN** - pěšiny	Paths Walkways Plazas	Other GI elements
Brownfields and transformation areas	**XD** - devastovaná území, deponie bez staveb, deponie **XP** - plochy bez využití - proluky **XZ** - nevyužívané plochy s nálety dřev	*Disused or devastated territories without constructions including landfills and different forms of vacant lots.*	
Agricultural lands	**PLP** - pole produkční **PLU** - pole - úhor	Arable lands Fallow lands	
Water bodies	**HY** - vodní toky a plochy	Water streams and objects	

From the perspective of delivering social benefits of urban green infrastructure accessibility of green space by citizens is another matter of importance. With regard to accessibility of an area the IPR has divided its land use data into 5 types. In relation to Prague green spaces, the author groups them under two categories: (a) public, and (b) restricted. Basically, the category of restricted access has included the spaces that had been defined in the original dataset as private, specialized, restricted, or unknown. The calculations of shares of Prague green spaces according to their accessibility are presented in the practical part in a table view. Besides, publicly accessible green spaces are reviewed from the perspective of their types (Table 4.2.1) indicating the amount of publicly accessible green spaces while excluding private and restricted green infrastructure segments. The results of calculations are presented by the table and pie chart. The distribution of public green spaces is also illustrated as a layer at one of the outcome maps.

A majority of pedestrian areas and sidewalks, which are considered as a separate land use type in the classification by IPR, are in fact integral parts of parks and urban forests. Some of them that are not directly related to green spaces are still considered as green infrastructure assets as suggested by different classifications that are mentioned in Chapters 3.1 and 3.2 of the present work. For this reason, the area of publicly accessible pedestrian areas is also calculated and presented.

Topography might present another form of limitation of accessibility of green infrastructure. Moreover, slope gradients of cycle routes are often mentioned among some of the most influencing factors in people's decision to use a bike (Winters et al., 2011). Landscape of Prague can be characterized by a relatively large area occupied by steep slopes, and it is fair to suggest that the distribution of green infrastructure often correlates with them. To look over the role of terrain in the distribution of green spaces and popular cycle routes another GIS analysis has been implemented.

A digital terrain model of Prague has been downloaded as a raster with 1x1 m resolution from the open data presented by the IPR and analysed using GIS. The steepness of slopes is counted by the *'Slope'* tool represented in percentage of gradient, where a 45° slope corresponds to 100% gradient. The level of slope steepness has been classified on a basis of feelings that cyclists might experience while climbing it (Table 4.2.2) (The Climbing Cyclist, 2013).

Spatial distribution of steep slopes across the city is represented by a raster map created on the basis of above-mentioned data. In order to quantify the terrain characteristics in publicly accessible green zones the raster map has been clipped by a vector layer indicating the green spaces that have no restrictions of access by citizens (*'Clip raster by mask layer'* tool).

Also, since the majority of pedestrian spaces and walkways are considered as green infrastructure and located within the area of green spaces, the vector layer with publicly accessible pedestrian areas has been also applied over the raster that contains slope gradient data. This step made it possible to calculate the shares of areas of green spaces including pedestrian paths according to the steepness of slopes. Additionally, the map indicating spatial distribution of public green spaces and its correlation with the character of terrain is created.

Table 4.2.2 Classification of gradients in accordance with estimated feelings that cyclist might experience when climbing it

Gradient	Estimated feelings from climbing by bicycle
0-0,99%	A flat road
1-3,99%	A slight unchallenging ascent
4-6,99%	A manageable uphill that can cause fatigue over long periods of ride
7-9,99%	Uncomfortable gradient that would be challenging for beginning riders
10-14,99%	Unpleasant incline which is very likely to force a cyclist to dismount after short period of ride
>15%	A climb by bike is painful and rather impossible for any length of time

Figure 4.6 Examples of steep gradients in Prague:
A - 12% gradient at U Rajské zahrady street that goes along the edge of Rajská Zahrada Park in Žižkov neighborhood
B - a short uphill section of mixed-use path with a very steep gradient (~12-15%) near Pohořelec tram stop in Hradčany (Credits: author)

Thus, three major steps are made in order to assess Prague green infrastructure:

- Classification of green spaces and other green infrastructure elements has been applied based on the Prague land use data. The shares of different categories of green infrastructure are calculated and their distribution is mapped.
- Based on accessibility green spaces are divided on the public and restricted ones. The shares of different types of green spaces according to their accessibility are also presented. Besides, the distribution of public green spaces is mapped.

- The terrain of the city is evaluated in terms of slope steepness. Gradients are classified with respect to the difficulty of climbing them by the average bike rider. The shares of publicly available green spaces are counted according to their relief conditions, and the map showing the correlation between topography and publicly accessible green spaces is created.

Combination of calculations and maps resulted from the research of both cycling and green infrastructures makes it possible to correlate both systems, identify the gaps in the network of cycle routes, categorize green spaces according to their role in cycling at a city-scale and cycling conditions they provide. Visual representation of that correlation is illustrated at the last outcome map that indicates the distribution of green infrastructure assets including publicly accessible green spaces, agricultural lands, brownfields, and pedestrian zones along with the distribution of frequently used cycle routes with illustrated level of their physical separation from motor traffic. This map helps identify the gaps in the designated bikeways, specify major green infrastructure elements that play an important role in terms of safe cycling and analyze them on this matter. Besides, the map illustrates marked segregated routes within designated bikeways that have not been identified as frequently used. The notable examples of green spaces and some of identified gaps in the bikeway network will be discussed in the Discussion chapter of this present thesis.

5. Results

5.1 Transport conditions and intensity of use of cycle routes

The system of Prague cycle routes consists of almost 1350 km of bikeways. However, at the end of 2020 only around 520 km of designated routes were marked with signs (Table 5.1.1). The process of installing new navigation signs along the routes continues constantly.

Table 5.1.1 Shares of marked bikeways along designated cycle routes system

Marked routes	Unmarked routes	Total	
520,47	828,27	1348,73	km
38,6%	61,4%	100%	%

Nonetheless, in terms of safety of users, physical conditions along the bikeways are a more important factor. The system of bikeways includes different types of cycle routes located among various traffic conditions. Those were divided under two groups: (a) in-roadway bikeways, and (b) non-motorized traffic paths. Calculations of lengths indicate that over 60% of all designated cycle routes in Prague share the roads with motor traffic including more than 40% of the bikeways that have no any physical separation from vehicles. Segregated non-motorized paths make up 39% of designated bikeways with almost 500 km of mixed-use paths and 25 km of separated bike paths (Table 5.1.2, Figure 5.1).

The actual distribution of commonly used routes might not totally match the system of designated bikeways. As described in the Methodology chapter, in order to evaluate the level of correlation between actively used cycle routes and the bikeway system of Prague, a separate dataset showing distribution and length of frequently used routes has been created. Their identification is based on the street-level cycling intensity analysis performed by the Umotional Analytics (Umotional, 2019).

In total, 498 km of cycle routes were identified as either primarily or secondarily used by cyclists. The calculations show that 433 km of them are part of the designated cycle network (32,1% of all bikeways), while 66 km are not.

96% of primary (224,64 km) and 78,6% of secondary (208,37 km) routes match officially designated bikeways. In contrast, 9,27 km of primary and 56,62 km of secondary routes do not coincide with the bikeways network. In average, 86,8% of all frequently used bikeways correspond with the system of designated cycle routes.

The evaluation of physical conditions along commonly used cycle routes has shown that among primary routes the paths for non-motorized transport modes have had almost the same share as in-roadway bikeways (47,6% vs. 52,4% of all primary routes respectively) (Table 5.1.3, Figure 5.2), despite their lesser presence in the network (Table 5.1.2).

Table 5.1.2 Physical separation of designated cycle routes from other traffic

In-roadway bikeways				
No separation	Bike lanes	Traffic-calmed streets	Total	
568,70	89,78	163,52	**822,00**	km
42,2%	6,7%	12,1%	**60,9%**	%
Non-motorized traffic paths				
Mixed-use paths	**Bike paths**	**Dismount**	**Total**	
499,15	25,31	2,27	**526,73**	km
37,0%	1,9%	0,2%	**39,1%**	%

Table 5.1.3 Physical separation of primary cycle routes that are part of designated bikeways

In-roadway bikeways				
No separation	Bike lanes	Traffic-calmed streets	Total	
84,68	17,68	15,28	**117,64**	km
37,7%	7,9%	6,8%	**52,4%**	%
Non-motorized traffic paths				
Mixed-use paths	**Bike paths**	**Dismount**	**Total**	
98,83	8,17	0,00	**107,00**	km
44,0%	3,6%	0,0%	**47,6%**	%

Table 5.1.4 Physical separation of secondary cycle routes that are part of designated bikeways

In-roadway bikeways				
No separation	Bike lanes	Traffic-calmed streets	Total	
101,65	14,41	18,91	**134,97**	km
48,8%	6,9%	9,1%	**64,8%**	%
Non-motorized traffic paths				
Mixed-use paths	**Bike paths**	**Dismount**	**Total**	
68,01	5,24	0,15	**73,40**	km
32,6%	2,5%	0,1%	**35,2%**	%

Nonetheless, the length of segregated paths among secondary routes is almost twice lower than those shared with vehicles (35,2% vs. 64,8% of all secondary routes respectively) (Table 5.1.4, Figure 5.3). Bike lanes and bike paths are the only types of bike infrastructure that have higher shares in both primary (7,9% and 3,6% respectively) and secondary (6,9% and 2,5%) routes than their shares in the whole network of designated cycle routes (6,7% and 1,9%).

Calculated length and shares of different types of cycle routes in designated bikeways and primary or secondary routes are graphically illustrated in the charts at Figures 5.1, 5.2, and 5.3.

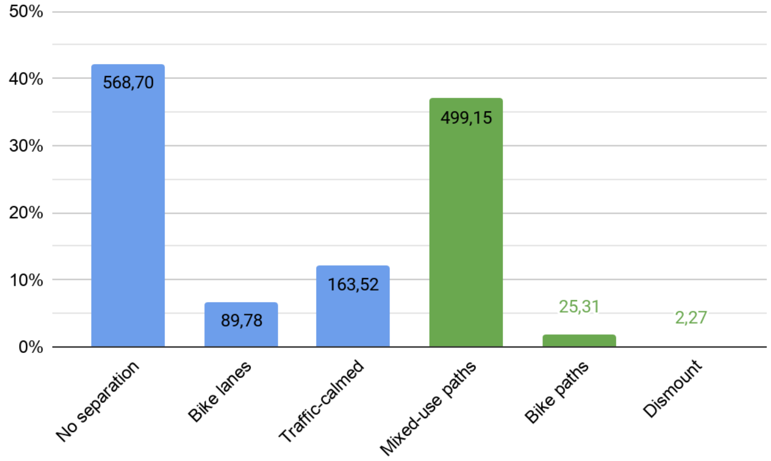


Figure 5.1 Shares and lengths (km) of different types of designated cycle routes according to transport conditions

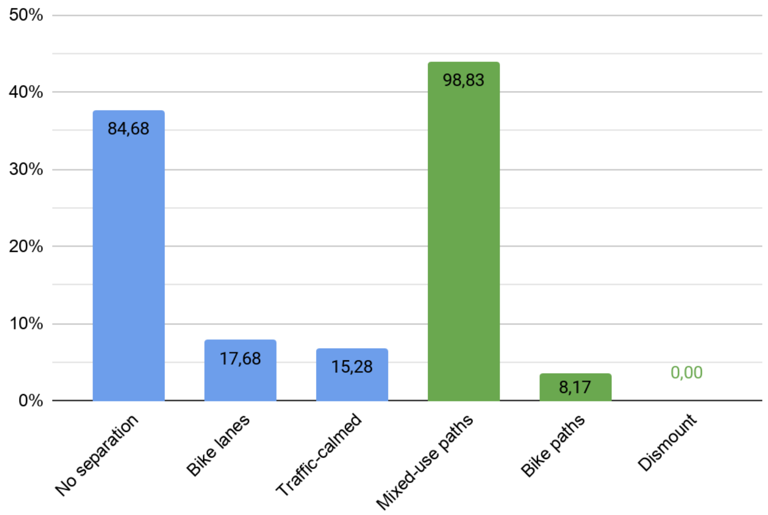


Figure 5.2 Shares and lengths (km) of different types of primarily used cycle routes according to transport conditions

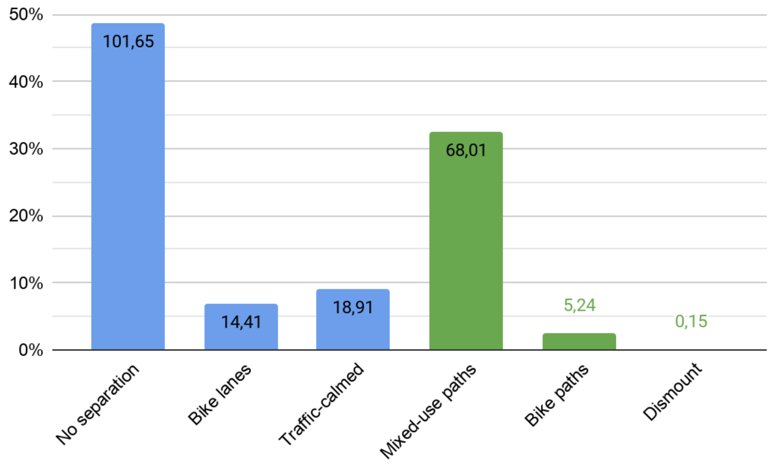


Figure 5.3 Shares and lengths (km) of different types of secondarily used cycle routes according to transport conditions

The map indicating spatial distribution of frequently used cycle routes with respect their order is presented in Appendix 3 of the present work. Figure 5.4 contains its segment illustrating the distribution of primarily and secondarily used cycle routes in the city center of Prague along with the distribution of green spaces and bike counters used for analysis.

Figure 5.4 Distribution of primary (red) and secondary (pink) cycle routes and bike counters in Prague city center (segment of the map from Appendix 3)

The data from 19 bike counters installed across the city (Golemio, 2020) made it possible to calculate the daily average number of riders passing by particular locations during the warm season in 2020 (from April to September). The distribution of detected rides according to a time of week allows to count the ratio between weekdays and weekends. The ratio helps supposedly identify, which locations are predominantly used for recreational purposes during weekends and which for utility rides on weekdays. The results of calculations are presented in Table 5.1.5, and the detailed review of count may be found in the table in Appendix 2. The locations of all 19 bike counters used for analysis are indicated on the map in Appendix 3 along with the distribution of Prague major cycle routes and publicly accessible green spaces. The example of its part showing the center of the city is also presented at Figure 5.4. The analysis of gained results will be reviewed in the Discussion chapter.

Table 5.1.5 Daily average number of rides detected by bike counters

id	Bike Counter	Route	Weekdays	Weekends	Average	Weekdays: weekends ratio
1	Modřany	A2	1664	2191	1927	43:57
2	Lahovičky (Strakonická)	A1	1170	1719	1444	40:60
3	Barrandovský most	A12	1388	1221	1304	53:47
4	Rohanské nábřeží	A2	1625	1013	1319	62:38
5	Povltavská	A2	1990	2446	2218	45:55
6	Stezka okolo Rokytky	A26	1127	1037	1082	52:48
7	Hlubočepská	A12	1047	999	1023	51:49
8	Krč (Sulická)	A22	949	828	889	53:47
9	Podolské nábřeží - stezka	A2	1191	689	940	63:37
10	Nábřeží Kapitána Jaroše	A1	873	470	671	65:35
11	Dukelských hrdinů	A310	611	398	505	61:39
12	Drážní stezka - Vítkov	A25	755	553	654	58:42
13	Podbabská	A1	795	930	862	46:54
14	U Českých loděnic	A2	1691	1431	1561	54:46
15	Kampa	A1	659	312	486	68:32
16	V Zámcích	A2	1469	1786	1628	45:55
17	Císařský ostrov	A310	520	535	527	49:51
18	Hybernská	A25	386	280	333	58:42
19	Nuselský most	A41	389	193	291	67:33

5.2 Urban green spaces and their qualities

As described in Methodology, this present research categorizes green infrastructure of Prague on a basis of land use types determined by the Prague Institute of Planning and Development (IPR Praha) and its land use dataset. The calculations of area occupied by different categories of green infrastructure show that green open spaces occupy 22767 ha, which is 62,2% out of 36582 ha of the total area covered by the green infrastructure. The most common type of green space is gardens and grassland, the share of which in the total area of green infrastructure is nearly a quarter. It is followed by forests and forest parks with 15% share, recreational spaces and parks (11,7%), and thickets and road verges (11%). Another extensive category of Prague green infrastructure is agricultural lands, which cover over 30% of its total area. Water objects, transformation areas (brownfields) and pedestrian zones cover 7,2% of the green infrastructure area altogether. The areas and shares of different types of green infrastructure are presented in Table 5.2.1 and illustrated in the chart at Figure 5.5.

A spatial pattern of distribution of green infrastructure elements by their types across the city can be seen at the map presented in Appendix 4.

Table 5.2.1 Types of green infrastructure

Type of Green Infrastructure	Area (ha)	Share (%)
Urban Green Spaces:	**22767**	**62,2%**
Forest parks	5501	15,0%
Thickets and road verges	4018	11,0%
Recreational spaces and parks	4298	11,7%
Gardens and grasslands	8951	24,5%
Pedestrian zones	618	1,7%
Brownfields and transformation areas	1001	2,7%
Agricultural lands	11181	30,6%
Water bodies	1014	2,8%
Total	**36582**	**100,0%**

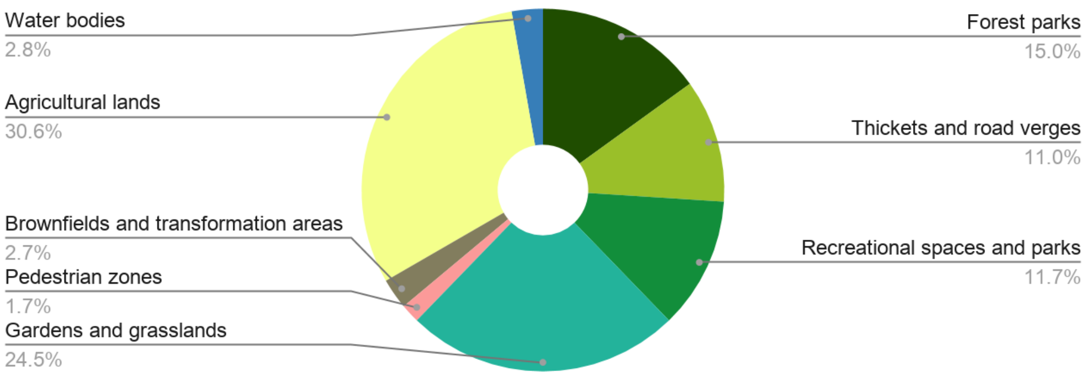


Figure 5.5 Shares of different types of green infrastructure in its total cover area

Green open spaces are those elements of green infrastructure the role of which in terms of development of cycling is the most essential. Nonetheless, their availability to citizens can be limited. The accessibility of green spaces has been categorized in the IPR dataset under 6 groups, which the author generalizes into two large groups with respect to general availability of green space for citizens: (a) public, and (b) restricted. The share of green spaces without any restrictions applied is over 61%, while almost 39% of green spaces are either private or having restricted access. The shares of each category of green spaces in terms of their availability for the public are presented in Table 5.2.2.

Distribution of all publicly accessible green spaces without regard to their types is indicated on the map in Appendix 3 along with the frequently used cycle routes and bike counters. Also, the above-mentioned Figure 5.4 illustrates the segment with the central part of Prague as presented in that map.

Table 5.2.2 Accessibility of urban green spaces

Accessibility of Green Space	Area (ha)	Share (%)
Public	13920	61,14%
Restricted	413	1,81%
Private	7957	34,95%
Specialized	470	2,06%
Unknown	4	0,02%
Undefined	3	0,02%
Total	**22767**	**100,00%**

In terms of types of green space, the largest publicly accessible category is forests and forest parks. Only 174 ha of all urban forests fall under private or restricted access. In contrast, over 7000 ha of gardens and grasslands are privately owned and having a limited access, what makes this category the least presented among available urban green spaces. The areas and shares of each category of publicly accessible green spaces are presented in Table 5.2.3 and illustrated in the chart at Figure 5.6.

Table 5.2.3 Types of publicly accessible green spaces

Type of Green Space	Area (ha)	Share (%)
Forest parks	5384	38,7%
Thickets and road verges	3697	26,6%
Recreational spaces and parks	2903	20,9%
Gardens and grasslands	1935	13,9%
Total	**13920**	**100,0%**

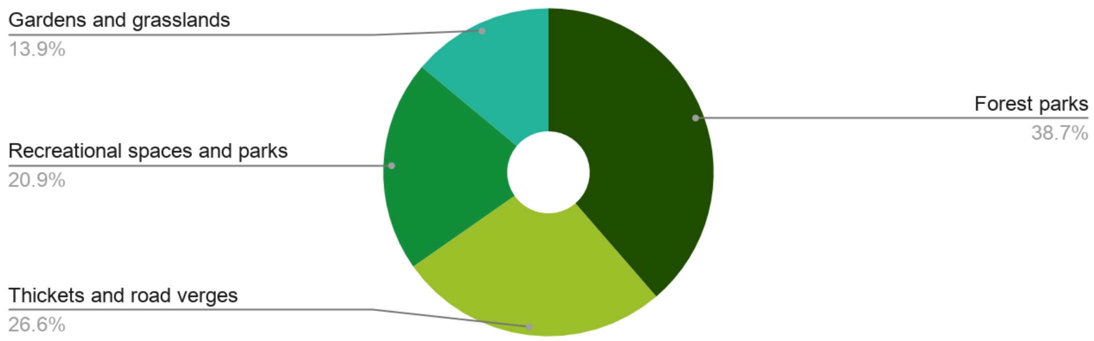


Figure 5.6 Shares of different types of publicly accessible green spaces

Pedestrian areas and sidewalks, as being an integral part of green infrastructure and green spaces particularly, are also calculated from the perspective of their accessibility. Counts show that 597 ha out of 618 ha of all pedestrian areas have no restrictions and are publicly accessible. Hence, in total, there are 14517 ha of green spaces and pedestrian areas that are considered public in terms of their accessibility.

The evaluation of public green spaces and pedestrian areas in terms of topography and slopes shows that over 30% of the assessed area are located on the slopes with 15 or more percent gradients, which are impossible inclines for climbing by bike. Nonetheless, over 35% of the area of public green spaces and pedestrian zones do not exceed 4% gradients, which are considered flat and unchallenging in terms of bicycling. The rest 34,2% of the area are situated within the zones with either slightly challenging gradients (4-7%) or unpleasant and often unbearable inclines (10-15%). The results of assessment of gradients are presented in Table 5.2.4 and illustrated in the chart at Figure 5.7.

Besides, the map illustrating the correlation between distribution of steep slopes and publicly accessible green spaces is presented in Appendix 5.

Table 5.2.4 Gradients within public green spaces and pedestrian zones

Gradient	Area (ha)	Share (%)
0 - 0,99%	791	5,5%
1 - 3,99%	4330	29,8%
4 - 6,99%	2374	16,4%
7 - 9,99%	1312	9,0%
10 - 14,99%	1275	8,8%
>15%	4435	30,5%
Total	14517	100,0%

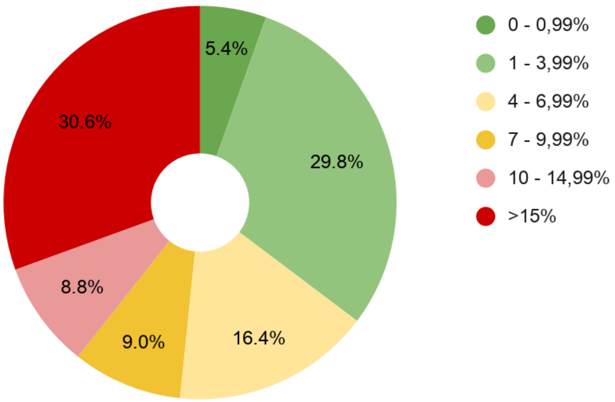


Figure 5.7 Steepness of slopes and their distribution across public green spaces and pedestrian areas

The GIS analysis applied to assess green infrastructure and cycle routes allowed the creation of the map presented in Appendix 6. The map indicates the distribution of green infrastructure including publicly accessible green spaces and pedestrian zones along with the frequently used cycle routes illustrated according to their physical separation from motor traffic. The undefined cycle routes are those that are not part of officially designated bikeways. The map is showing the urban area of Prague excluding the suburbs where almost no identified major cycle routes are situated. The segments of this map will also be illustrated and discussed in the Discussion chapter as a part of reflections on the role and types of green spaces in terms of cycling development, its safety, and continuity of both cycling and green infrastructures.

6. Discussion

6.1 Hard infrastructure along cycle routes

The assessment of spatial distribution of frequently used bikeways and the level of their correlation with designated cycle routes shows that the majority of 96% of primarily used routes correspond with the official system of cycle routes, while the bikeways of the second order do not coincide with it in 21,4% of their length. The system of designated bikeways intends to suggest a relatively safe route as a substitution to busy streets with high speed limits. Nonetheless, a significant share in 66 km of gaps identified in the network of official bike routes are represented by in-roadway segments used as shortcuts in the areas where designated bikeways either (a) are not presented at all, or (b) indistinguishable in the landscape due to a lack of navigation signs or physical infrastructure, or (c) planned in a way that requires a cyclist to spend noticeably more time or energy when riding between major destinations. Some of the identified gaps will be discussed later as a part of reflection over configuration of green spaces and their correlation with the frequently used cycle routes.

The results of assessment of cycling conditions have also shown that at the level of primarily used cycle routes the length of non-motorized paths is slightly higher than the total length of in-roadway routes without infrastructure or with bike lanes only (excluding streets with calmed traffic): 107 km vs. 102,4 km respectively (Table 5.1.3). For comparison, the total length of separated paths in the designated bikeways is 133,7 km shorter than those without separation: 524,8 km vs. 658,5 km respectively. On the other hand, in contrast with primary routes the length of secondarily used bikeways with segregated paths is significantly lower (Table 5.1.4). At this level their total length is 42,8 km shorter than the length of cycle routes planned at the streets without physical infrastructure: 73,3 km vs. 116,1 km respectively. The difference would be even larger if those 66 km of frequently used routes that are not part of designated bikeways were counted. There might be two main reasons for such a big difference between two determined categories of frequently used bikeways.

The first reason may lie in an approach used by the author to categorize frequently used bikeways. The routes classified as primary include the segments with a wide range of intensity levels. As mentioned in Methodology, the author ranks as ‘primary’ those cycle routes that got over 100 average rides per day according to a cycling intensity analysis performed by the Umotional. This puts the routes with 200 average daily rides to the same level as those with 1000 or more. A wider range of selected categories of routes would lead to a less abrupt difference in the results showing a smooth transfer between determined categories allowing to compare them on the matter of presence of segregated infrastructure as well.

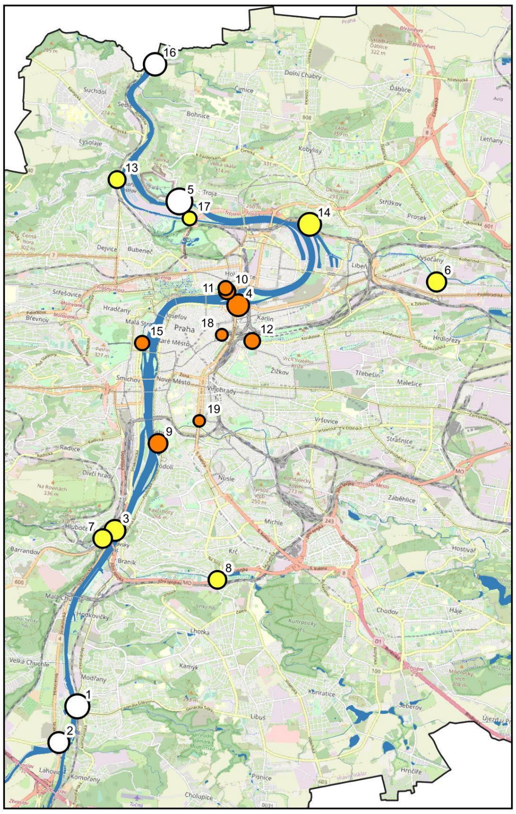
The second reason is a spatial distribution of segregated paths themselves. As we can see from the maps in Appendices 3 and 6, their arrangement in many cases coincides with the distribution of primary routes as many of them tend to follow either the Vltava riverbanks (A1 and A2 cycle routes) or the greenways along its major streams (e.g. A22 along the Kunratický stream, A26 along Rokytka). The configuration and structure of specific greenways will be discussed in more detail in the further sections of Discussion. It is appreciable nonetheless to mention that many of these green spaces originally had relatively good natural preconditions for accommodating the segregated paths and trails for non-motorized modes of transport. Thus, tens of kilometers of bikeways along the Vltava riverbanks and different greenways are used by thousands of cyclists everyday making these elements of green infrastructure a backbone of the cycle routes network. The kilometers of these predominantly separated bikeways are ranked as primary routes increasing their share in the whole network of popular routes. In the urban core of Prague almost all segments of separate paths that were not identified as primarily used routes are ranked as secondary. Thus, as it can be seen in Appendix 6 map, apart from a few segments almost every segregated cycle route which is located within the urban core is determined as a frequently used route of either primary or secondary level. The rest of separated paths are located at the outskirts of the urban area and are not used by so many cyclists in order to be classified as a major route.

The results of analysis indicated above do not include the ‘traffic-calmed streets’ category of cycle routes. Their role in cycling in Prague is somewhat controversial. As calculations show only 20,9% of routes designated to calm streets are determined as frequently used bikeways (34,2 out of 163,5 km) (Tables 5.1.2, 5.1.3, 5.1.4). In contrast, the share of actively used bike lanes is 35,7% and of bike paths is 53%. Apart from a few bikeways designated as traffic-calmed streets located in the neighborhoods of Dejvice, Holešovice, Kobylisy, and Budějovická metro station, a majority of cycle routes of this type lie in the periphery of the city connecting small settlements in the suburbs. Some sections of these roads are not used by vehicles at all, hence to a certain extent they can also be considered as paths predominantly for non-motorized users. Also, few of such segments are intensively used parts of A2 and A1 bikways. These sections lie on the city outskirts at the Vltava banks and are parts of important recreational cycling destinations. For instance, according to the calculations the southernmost bike counter installed at A1 cycle route at the junction of traffic-calmed street and mixed-use path in *‘Lahovičky’* (2) has a daily average of 1444 detected bike rides with the weekdays:weekends ratio determined as 40:60 (Table 5.1.5).

The data from bike counters processed by the author appears to have a fairly high value in terms of cycling research. For instance, as mentioned above, the river banks of Vltava accommodate A1 and A2 cycle routes that form a backbone of the system of bikeways. There is a difference in the intensity of use and physical conditions between these two though. As seen in Appendix 6, the A1 route that lies at the left bank of Vltava does not have long continuous paths segregated from the motorized vehicles. In Prague urban core this type of infrastructure is fractured and occurs only in a few segments of A1 route. In contrast, the A2 route comprises predominantly continuous and separated paths that get interrupted only at the section where the Old Town is closely adjacent to the river bank (Smetana and Masaryk embankments). Furthermore, the Smetana embankment soon expects the reconstruction, which will lead to construction of separate bike paths along it with exception of the narrow section by the Charles bridge that will remain on-road. Correspondingly to cycling infrastructure, the intensity of use of both sides of the river by cyclists is also significantly different. All 6 bike counters installed along the A2 cycle route have detected at a minimum 940 of daily average number of rides (*'Podolské nábřeží - stezka' (9)*) with at least 1191 rides in the weekdays. The highest number within all bike counters belongs to the camera trap at *'Povltavská'* (5) with 2218 of detected rides on average. In contrast, within four bike counters installed along the A1 route only the one in *'Lahovičky' (2)* has reached an average number of rides exceeding 1000 per day. At three other locations within A1 route this index ranges between 486 and 862 (Table 5.1.5).

Apart from the camera traps along A2 and A1 routes, there are three more locations with bike counters where a daily average number of rides exceeds 1000: *'Barrandovský most'* (3) and *'Hlubočepská'* (7) at the A12 cycle route, and *'Stezka okolo Rokytky'* (6) at the A26. It is worth mentioning that the *'Barrandovský most'* (3) counter is basically a continuation of the A22 cycle route, which is set at the right bank of Vltava and goes along the Kunratický stream (Appendix 3). In the season of 2020 the bike counter *'Krč'* (8) installed at that path has detected 889 rides in average per day. These high numbers identified in the locations that are situated relatively far from the city center and not exactly along the Vltava's A1 and A2 routes can be explained by the greenways they are part of. Following the water streams with smooth gradient and natural environment greenways create pleasant conditions that substitute a more stressful ride along busy streets or highways. The most important greenways of Prague will be discussed in more detail at the section of this chapter devoted to configuration and qualities of green spaces.

The calculated ratio that indicates the shares between the average numbers of rides detected by bike counters on weekdays and weekends also contributes to the perception of the structure of the cycling network in Prague. For illustration an additional map and table are created and presented in Figure 6.1. Based on the weekdays:weekends ratio index of evaluated bike counters, the locations are grouped under three general categories: (a) often used for recreation, with the >55% share of weekends in a daily average, (b) used universally, with a range of shares between 45% and 55%, and (c) often used for utility rides, with the >55% share of weekdays in a daily average. Also, the size of the symbols in the map in Figure 6.1 broadly represents the average number of rides calculated on the basis of the data collected by a bike counter (Table 5.1.5).



id	Bike Counter	Route	Weekdays: weekends ratio
16	V Zámcích	A2	45:55
13	Podbabská	A1	46:54
5	Povltavská	A2	45:55
17	Císařský ostrov	A310	49:51
14	U Českých loděnic	A2	54:46
6	Stezka okolo Rokytky	A26	52:48
11	Dukelských hrdinů	A310	61:39
10	Nábřeží Kapitána Jaroše	A1	65:35
4	Rohanské nábřeží	A2	62:38
12	Drážní stezka - Vítkov	A25	58:42
18	Hybernská	A25	58:42
15	Kampa	A1	68:32
19	Nuselský most	A41	67:33
9	Podolské nábřeží - stezka	A2	63:37
3	Barrandovský most	A12	53:47
7	Hlubočepská	A12	51:49
8	Krč (Sulická)	A22	53:47
1	Modřany	A2	43:57
2	Lahovičky (Strakonická)	A1	40:60

Figure 6.1 Weekdays:weekends ratio of the assessed bike counters

As mentioned above, the segments of A1 and A2 cycle routes that are located in the outlying areas are often used for recreational cycling. Besides that, all four locations where over 55% of the rides were associated with weekends belong to the segments of designated bikeways with the most intensive use on a daily average (Table 5.1.5). Thus, regardless of part of the week the role of the cycle routes along Vltava is crucial even if located on a remote distance from the city center. Also, a comparison of the data from A1 and A2 routes highlights a particular importance that lies in the presence of segregated paths for non-motorized users. Its occurrence along the A2 cycle route creates opportunities to use a bicycle for both recreation or utility rides among a wider range of population.

As seen in Table 5.1.5 and Figure 6.1, a significantly larger share of weekdays in weekdays:weekends ratio (>55%) in 2020 has been observed at 8 out of 19 evaluated bike counters. All of them are located in the city center or in a relative proximity to it. All of them, apart from the *'Hybernska'* (18) and *'Dukelských hrdinů'* (11) are allocated at the segregated paths for non-motorized users. The two bike counters that have detected the highest number of daily average rides are located at the right bank of Vltava at the A2 cycle route: *'Rohanské nábřeží'* (4) and *'Podolské nábřeží - stezka'* (9).

In terms of a spatial arrangement of bike counters mainly the main entrances to the city center are represented. Considering the dense network of streets in the center, the number and arrangement of bike counters there gives rather speculative and obscure information on the spatial distribution of commonly used bikeways. Introducing more counter cameras in other parts of the city center would most likely contribute to improved comprehension of the current state of cycling and the layout of cycle routes. This might have an especially relevant role as the character of urban cycling gradually changes towards a larger number of short-distance rides in the city center due to a growing popularity of bike-sharing (Filler, 2020). These and other issues of collecting data from bike counters and other limitations of cycling data that were used in the research are discussed in the next section of the chapter.

6.2 Limitations of acquired cycling data

As mentioned before, the identification of frequently used cycle routes in Prague has been based on the street-level cycling intensity analysis performed by the Umotional Analytics. The most recent presented data available in the online visualization of the results indicates the distribution of routes in 2019. A comparison of the average intensity of use of bikeways presented by Umotional for 2019 and the daily average number of rides calculated by the author on the basis of data from bike counters in 2020 demonstrates a disproportion between the datasets. In some locations differences between the data can reach up to a factor of four, but on average the values vary roughly in a range of 20 to 30%. A few reasons might be lying behind this disproportion.

Firstly, other analyses of the data from bike counters show an increase in intensity of cycling in Prague as much as 32% or more in just 2020 (Filler, 2020). Increased popularity of non-motorized types of transport in 2020 is a global trend, which is observed in most of the countries where the lockdown measures such as social distancing have been applied in order to reduce transmission dynamics of the COVID-19 infections (BBC, 2020).

The second reason might lie in the improved data gathering by bike counters. The error rate of the Camea counters has decreased from 13% to 8% according to Filler (2020). The historical overview of the data collected by bike counters presented at the Golemio platform also illustrates a significant number of outages and missing data that have been happening throughout 2019 (Golemio, 2020). This high amount of missing or failed data has also become a reason for the author of the present thesis to totally exclude 2019 from the calculations used for analysis of bike counters. Nevertheless, the data collected in 2019 have been used by Umotional in their analysis of cycling intensity along with their own data collected from the GPS records in a cycling application developed by the company (*‘Na kole Prahou’* - Prague by bike). This might have led to reduced numbers in the rates of intensity of bike use in their street-level analysis. In contrast, an improved methodology of camera trapping used in 2020 might have resulted in more accurate results indicating the intensity of use of cycle routes.

The third reason for large differences might be related to the sample of users of the application used by Umotional in the analysis. The application *‘Na kole Prahou’* is used by the participants of Bike to Work annual campaigns and is common within regular cyclists who use the application to plan their utility rides within the city area rather than occasional users who plan the recreational bike rides to the outskirts of the city. This premise might be proved by the fact that the largest identified differences between the data from bike counters and cycling intensity analysis were related to such locations as *'Povltavská'* (5), *'Lahovičky'* (2), *'V Zámcích'* (16). All these destinations have a significant share of the rides committed on weekends, supposedly for recreation purposes (Figure 6.1).

Although the numbers of average rides presented in the cycling intensity analysis appear to be underestimated, a spatial distribution of frequently used routes has been compared and checked by the author on the matter of correspondence with the heatmaps mentioned in the Methodology chapter. No significant discrepancies were identified, hence, the underestimated rates presented in the cycling intensity analysis most likely did not severely affect the outcoming depiction of spatial distribution of cycle routes.

Based on the provided above examples of obstacles within used data, it is appreciable to highlight that a comprehensive analysis of the intensity of use of cycle routes and their spatial distribution needs to involve multiple sources of information covering a wider range of users and including more accurate data in various locations. The use of bike counters for research gives a lot of valuable information especially in the course of longer periods of observation, but their technical conditions should be regularly maintained so the outages are prevented. The development of technologies in artificial intelligent systems and their use in traffic monitoring and other fields can help prevent the occurrence of misleading and inaccurate data. A comprehensive and thorough combination of datasets can help identify the gaps and interruptions in cycle routes, determine their actual load, compare their distribution with other elements of land use such as green spaces or, for instance, residential areas. The use of relevant and reliable data leads to less unbiased analysis of the current conditions of cycling in the city and is helpful in terms of planning of further investments and urban development.

6.3 Configuration and connectivity of green spaces and major cycle routes

As has been identified and mentioned above, a major part of frequently used cycle routes correlate with the distribution of green spaces, particularly with the Vltava waterfronts and greenways alongside its tributaries. According to the landscape ecology mosaic model the landscape elements can be grouped under three categories based on their structure and functions (Tables 3.2.2, 3.2.3). Patches, corridors, and matrices can be applied on urban green spaces in terms of their configuration and structure. The roles of these categories of green infrastructure in terms of cycling can also differ. For instance, urban green corridors, which can be represented by water streams followed by greenways including such land use elements as forests, parks, meadows, etc., are often used as transit bidirectional routes with or without linkages to surrounding areas. In contrast, urban green patches, which are represented by parks and forests, might accommodate different routes oriented in multiple directions and intersected within a green space. An attempt to categorize Prague green spaces in terms of their configuration and distribution of cycle routes with respect to a landscape mosaic concept is represented in the discussion below. The reflection includes the most evident examples of green spaces that play an essential role in the patterns of use of cycle routes and it often refers to the maps presented in Appendices.

6.3.1 Greenways

An important role of Prague greenways and their correlation with distribution of cycle routes is evident. Historically, cycling in Prague can be characterized by a large share of relatively long-distance bike rides between neighborhoods and the city center (Filler, 2020). In these terms greenways perform an exceptional role of some of the most valuable links connecting remote neighborhoods with the city center. Also, they are commonly used as destinations for recreation.

There are 4 streams that are followed by the cycle routes that were ranked as primary in this research:

- Rokytka river accommodates the A26 cycle route;
- Dalejský stream forms a gorge known as the Prokop valley, which is used by cyclists who take the A12 route;
- Kunratický stream is followed by the A22 route;
- Libušský stream accommodates the cycle route A21.

Besides, the Šárecký stream in the northeast of the city forms the gorge that accommodates the A17 cycle route that has been identified as secondary. The Šárecký and Kunratický brooks are situated at the left bank of Vltava, while three others are located at the right bank.

A greenway formed along the Rokytka river creates an intensively used connection represented by the continuous segregated paths as part of the A26 cycle route (Figure 6.2). The bikeway connects multiple neighborhoods within administrative districts Prague 20, Prague 14, Prague 9, and Prague 8, creating a link between the city center and its northeast. This is one of the most commonly used cycle routes in the city. The data from the *‘Stezka okolo Rokytky’* (6) bike counter shows that over 1082 rides on a daily average are committed at the surveyed segment of the path (Table 5.1.5). 52% of daily average rides are taken on weekdays what determines this segment of the route as universal in terms of weekdays:weekends ratio (Figure 6.1).

Figure 6.2 indicates the arrangement of public green spaces along the Rokytka river and frequently used cycle routes in this area. The legend applied to Figure 6.2 corresponds to the one in Appendix 6. Additionally, the white dashed lines were added in order to show the distribution of other designated bikeways that were not identified as frequently used.

There are few gaps identified in the designated bikeways related to this area. At Figure 6.2 they are indicated by numbers 1 and 2. Number 1 illustrates the example of a few sections of cycle route along the Rokytka river in the Smetanka forest park area that are used frequently instead of designated bikeways. Their presence in that area can be explained by poorly developed cycling infrastructure and lack of navigation markings along the segments that are specified as designated routes. The gap indexed by number 2 illustrates an example of the shortcut used by cyclists who prefer to ride along the Sokolovská street towards Palmovka instead of having a curve along the greenway. Nonetheless, according to the Umotinal cycling intensity analysis the number of bicyclists using this shortcut is approximately 10 times lower than those who prefer to ride by the segregated path along the river.

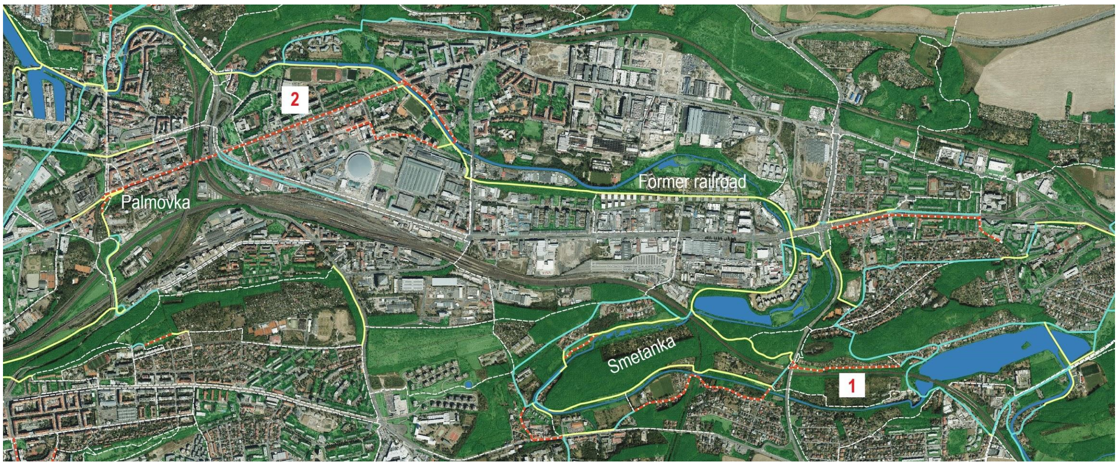


Figure 6.2 Rokytka river and the A26 cycle route

Two other major green corridors mentioned above are related to the streams in the southeast and southwest of the city. Cycle route A22 follows the Kunratický stream linking the A1 and A2 bikeways with the Kunratický forest and Chodov neighborhood (Figure 6.3). The daily average number of rides at this route ranges from 889 at the *'Krč'* (8) bike counter to 1304 at the *'Barrandovský most'* (3) (Table 5.1.5). At both counters the share of daily average rides occurring on weekdays have been identified as 53%. The bikeway itself consists predominantly of continuous segregated paths with a few on-road segments. The Kunratický forest is an important recreational destination in the southeast of Prague, which includes few separated bike paths. One of them is following the brook while few others link the Chodov neighborhood with the greenway situated in the valley. Besides, the forest is designated as the regional biocenter according to the territorial system of ecological stability. The absence of identified gaps within designated bikeways highlights their relevancy and integrity of the route itself.

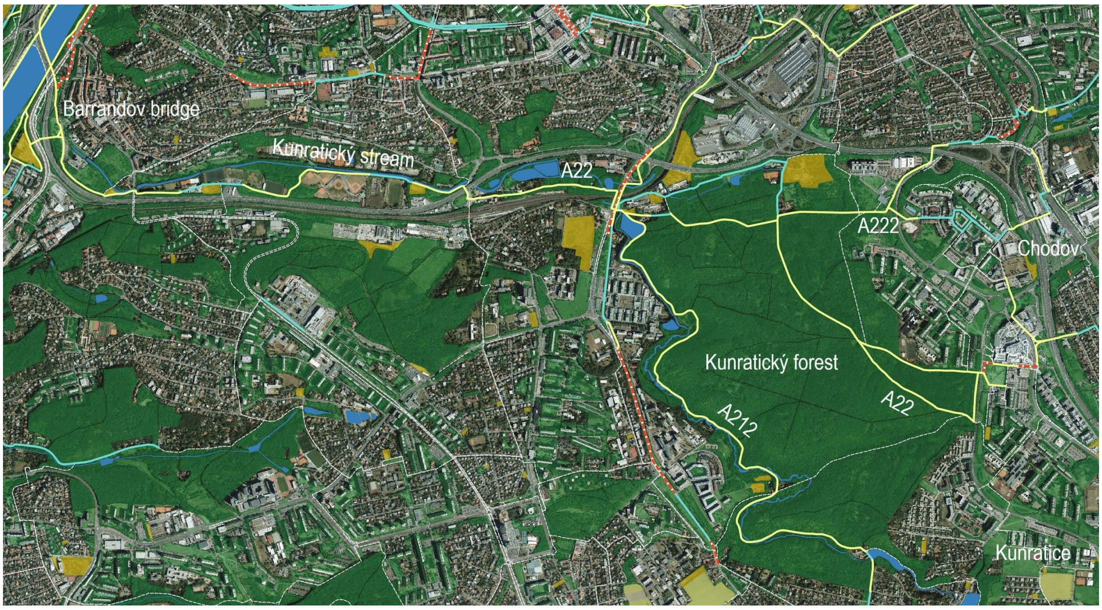


Figure 6.3 Kunratický stream and the cycle routes A212 and A22

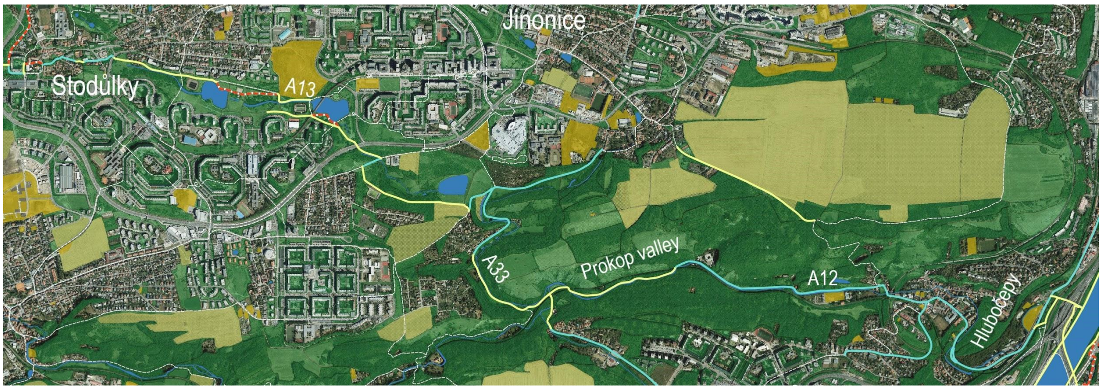


Figure 6.4 Distribution of A12 and A13 cycle routes along the Prokop valley and Central park in Stodůlky neighborhood

The Prokop valley is another gorge intensively used by cyclists for both recreational and utility rides. The weekdays:weekends ratio has been identified here at the *'Hlubočepská'* (7) bike counter as 51:49. On average around 1023 rides have been detected daily by this bike counter, which is installed at the junction of A12 and A1 routes (Appendix 3). Located at the left bank of Vltava it is the only greenway that is used at the level of the primary route. The A12, A13 and A33 bikeways are used as links between the Stodůlky and Jinonice neighborhoods and Vltava waterfront (A1 route). In contrast to the Rokytka and Kunratice, the Prokop gorge is surrounded by steep slopes which makes it impossible to link the bikeway with other routes around (Appendix 5). Another difference lies in the absence of a separate path along most of the route in the valley. The road however is a dead-end and barely used by vehicles in most of its length besides the 1 km section in the mouth of the valley located in Hlubočepy. Hence, a major part of the route is separated from motor traffic and may be considered as safe as segregated paths.

Not all major Vltava tributaries accommodate the green infrastructure that functions as a green corridor efficiently. One of such examples is the Botič stream that flows from the southeast towards the city center through multiple neighborhoods. In many sections the brook is followed by the A23 cycle route (Figure 6.5). The intensity of use associated with its segments corresponds to the level of primarily used routes (Appendix 3).

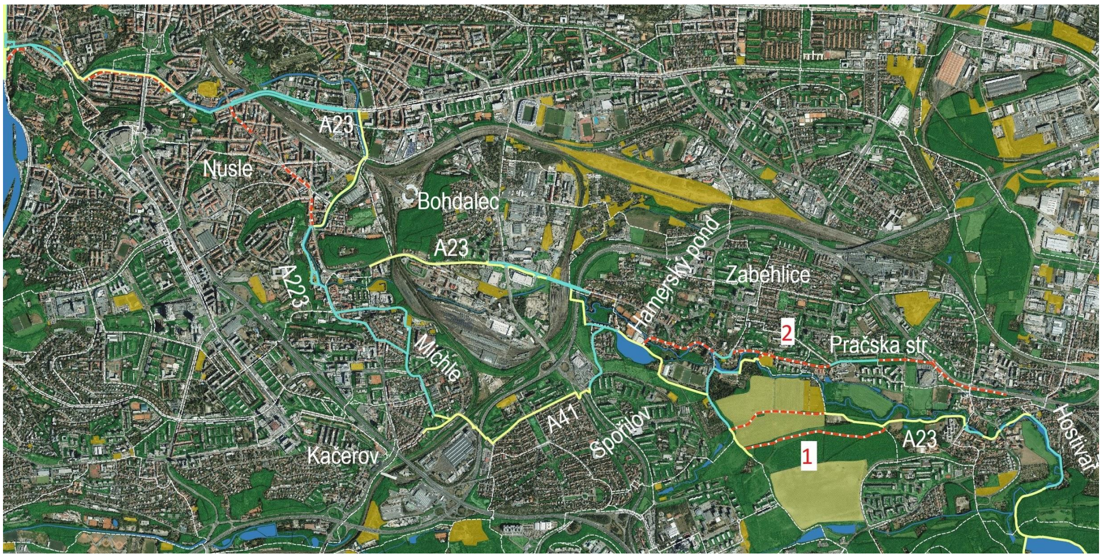


Figure 6.5 Botič stream and the fragments of A23 and other cycle routes

There are no active bike counters installed along these routes, but it is rational to suggest that the weekdays:weekends ratio would have a lower share of recreational weekend rides in comparison to the greenways stated above due to a lack of continuous and safe segregated paths for non-motorized traffic as the absence of it limits the possibilities to use infrastructure by a wider range of population, particularly families with kids and elderly people. Distribution of separated paths in this area has a fractured and unsystematic character. The brook itself is also crossed by the railroads and highways in multiple spots.

Besides, few exemplifying gaps in the designated bikeways can be noticed within the stream watershed. On Figure 6.5 the gaps indicated by number 1 show the shortcuts that a majority of cyclists use avoiding a curve through the waterfront of Botič that lies a few hundreds meters to the north from the path. Two alternative routes commonly used by cyclists are going through either an agricultural field or a disused garden. The second identified gap in the watershed of Botič lies at the Pračská and Zaběhlická streets. Eventually, these on-road sections of frequently used cycle routes join the segregated mixed-use path of the A23 cycle route near the Hamerský pond.

The absence of hard and continuous infrastructure along the Botič stream, the lack of navigation signs or markings, and irrelevant distribution of designated bikeways may be propounded as the reasons for such a fragmentation of cycle routes that lie in this area. The interruptions of the greenway caused by industrial and rail infrastructures do also limit the possibilities of this area to function as a green corridor. Nonetheless, the stream and cycle routes along it bear a potential of becoming another greenway in Prague that would link multiple neighborhoods (Záběhlice, Spořilov, Bohdalec, Kačerov, Hostivař are some of them) with the city center.

6.3.2 Rail-trails

Besides the segregated segments of cycle routes along the Botič stream, the dwellers of Záběhlice, Bohdalec, Hostivař, and other neighborhoods of Prague 10 will get another possible way to cycle through a safer environment by 2024. A construction of the projected Vršovická promenade should begin in 2022 (Filler, 2020). The 4,5 km promenade will replace a former section of the railroad that lies between the communities of Hostivař and Vršovice. This is an ambitious project of an exceptional 4-meters wide cycle path along with the boulevard for pedestrians and trails for joggers. The implementation of the project will have an impact on the distribution of non-motorized traffic in the southeast of Prague, including the above-mentioned A23 route, that lies to the south from the promenade, and the frequently used on-road cycle route with the bike lanes in the Vršovická street that lies to the north from it (Figure 6.6).

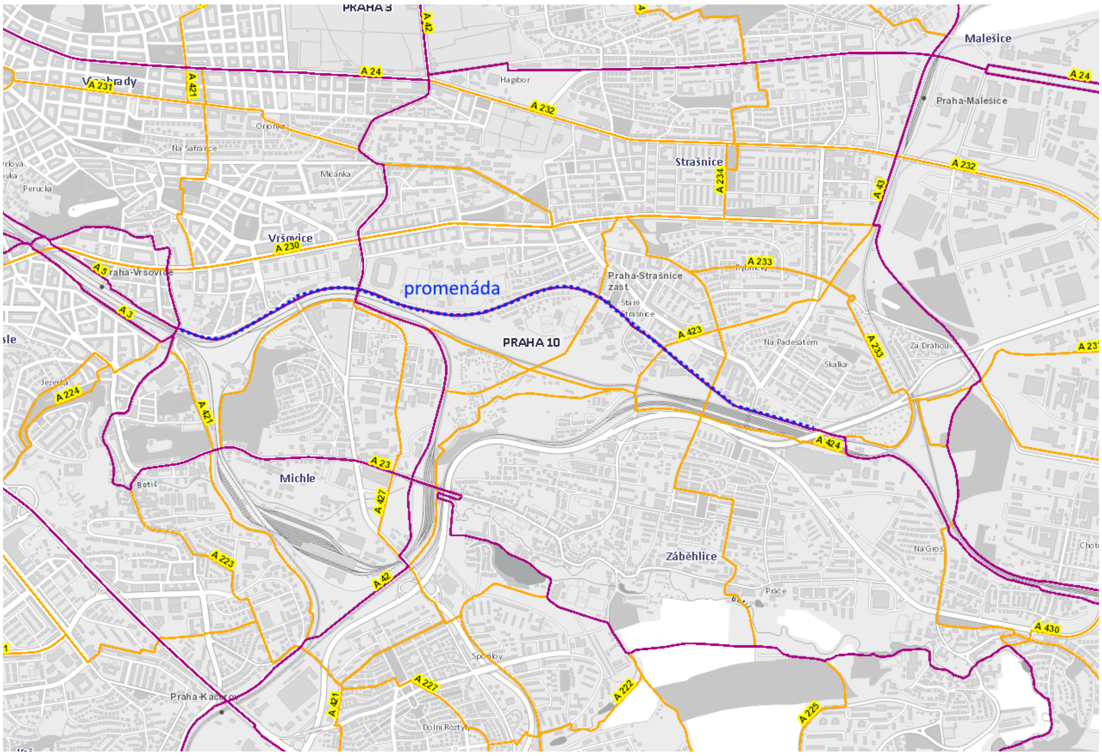


Figure 6.6 Vršovická promenade project (IPR Praha map; Source: Městem na kole)

The effectiveness and relevance of the planned promenade nevertheless depends from many technical aspects of hard infrastructure and other factors such as quality and number of links and connections with the residential areas around. The straight section of A26 Rokytka bikeway (Figure 6.1) has also substituted a former railroad in 2009 and many lacking connections of the path have been detected since its implementation (Motýl, 2019). The experience and mistakes that have occurred in that case should not be neglected in order to increase the potential of use of the projected Vršovická promenade.

A more well known implemented project of the rail-trail in Prague is located in the vicinity to the city center. Cycle routes A25 and A257 lie alongside the Vítkov hill, which is located to the east from the Old Town. The cycle route is represented by a mixed-use path all along the southern side of the hill and includes the Old Vitkov tunnel with a separated bike path that leads the route to the northern side and further to the Krejcarek forest (Figure 6.7).

Figure 6.7 The Vítkov hill and cycle routes A25 and A257 (Vítkov bike path)

The cycle route today is an essential link between the city center and Žižkov neighborhood. The bike counter installed in the western part of the path closer to the city center (Figure 4.4, Appendix 3) has detected 654 rides on a daily average in 2019 with a weekdays:weekends ratio identified as 58:42 (Table 5.1.5). Nonetheless, only a short section of the path is used that frequently. After two links to Žižkov the path's load drops to the level of the secondary route.

A complex topography and densely built area with land ownership obstacles along the Vitkov route create limitations in possible linkages with adjacent residential areas. Nonetheless, some projects of new connections exist and their implementation is expected. For instance, a Bicycle Master Plan of Prague includes a projected path that would link the A25 route with the Husitská street and, farther, the Florenc bus station. The area is currently occupied by the rail infrastructure, including the historical buildings of the traction substation Krenovka (Figure 6.8).

Nonetheless, one of the main weaknesses of the green corridor and cycle route in its current state is an absence of safe connections with other separated bike paths in its both ends. The section of Seifertová street where the path begins encompasses an unsafe and busy intersection that lacks segregated cycling infrastructure (*'Bulhar'* at Figure 6.7). The extension of the path in this direction would require a number of complex technical solutions for reconstruction of this intersection. Also, a Bicycle Master Plan suggests to extend the path towards the south through the current transformation area located at the backside of the main train station and link it with the Vinohradská street and National Museum.

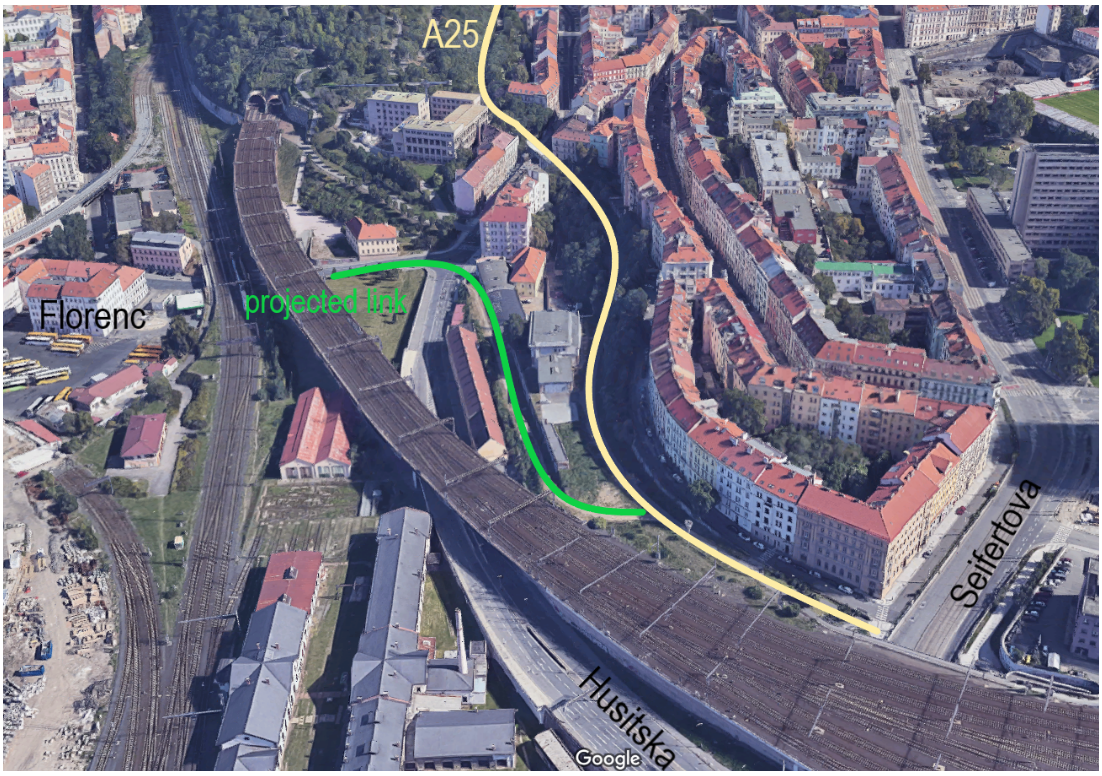


Figure 6.8 A projected link that should connect the A25 Vitkov bike path with the Husitská street via Krenovka (Image from Google Earth; Credits: author)

Another end of the Vitkov path located in Krejcarek continues with the secondary cycle route on the narrow sidewalk towards Palmovka. A steep gradient and noisy highway make this part of the path unpleasant and difficult to ride by. Furthermore, the segregated A2 cycle path along Vltava creates a safer environment for cyclists and connects Palmovka with the city center, so the Vitkov bike path as an alternative route for these destinations is usually neglected. Nonetheless, there are some proposals of the extension of the Vitkov bike path that might impact the relevance of this route and increase its relevance for local cyclists (Figure 6.9). For instance, a Bicycle Master Plan suggests a creation of a segregated path that would connect the A257 and A25 routes with the A26 Rokytka route mentioned earlier. A path would follow the railroad and pass the Liben train station. Such a solution would improve the linkage of the route with the public transit system and avoid steep gradients on its way. However, an implementation of such a project would require a lot of investments and time. An alternative connection can be also proposed on the basis of the current system of cycle routes. A creation of such a link between the A25 and A26 would require less time as reconstruction works would involve surfacing and lightning of the mountain-bike trail in the eastern part of Krejcarek forest and physical improvements along the sidewalk of the Spojovací street. Both proposals are depicted at Figure 6.9, where a path proposed by the Bicycle Master Plan is indicated by red markers and an alternatively proposed connection by green.

Figure 6.9 Proposed connections to link the Vitkov bike path and Rokytka greenway

Apart from the mentioned rail-trail projects in Vršovice, at Vitkov, and along Rokytka, there are other proposals of transformation of former railroads into non-motorized paths. For instance, one of them lies a few hundreds meters away from the Rokytka bike path and located in the Malešice forest park. The transformation of the rail into a cycle path would improve the segregated connection between the A26 Rokytka bike path and Žižkov neighborhood. The realisation of such a project however requires a proper attention and incorporation into the plans of development of the Žižkov cargo train station, which is one of the largest brownfields in the vicinity to the city center.

One more project of a rail-trail is related to the railroad in the Holešovice neighborhood. The section of the on-ground railroad Prague-Kladno that goes from Stromovka park towards Letná should be replaced by an underground tunnel, so a green corridor would appear in its place. This would create a possibility to have a segregated connection between two valuable and major green spaces in Prague 7 that are, besides, commonly used by cyclists.

Based on the described above projects, it is possible to state that the former railroads are becoming reasonably important land use elements in terms of cycling network development. Often situated in the green zones such as forests and parks their transformation into green corridors for non-motorized users can bring more connectivity into the network of cycle routes. Furthermore, the lack of steep gradients along the railroads is one of the essential factors in terms of cycling as well. The implemented projects of the rail-trails at A25 and A26 cycle routes show that the number and quality of links between a path and residential neighborhoods is crucial for further development of the green corridor and intensity of its use by non-motorized users.

6.3.3 Recreational parks and forests

Apart from the greenways and green spaces along rails-trails that can be considered as green corridors in terms of landscape ecology mosaic model, there are green spaces that are associated with urban patches such as parks and recreational areas, which are frequently used by cyclists and play an essential role in distribution of separate cycle routes. Both Stromovka and Letná parks are located in the northern part of the city in Prague 7 municipality and accommodate some of the most important bikeways connecting the city center with the north and northwest of Prague (Figure 6.10). Both parks are characterized by relatively large areas with flat terrain and presence of steep gradients in their southern parts (Appendix 5). The steep slopes of Letná are commonly used by cyclists as primary routes since this area provides an appreciable time-saving shortcut on a way from the city center towards west and northwest of Prague. In contrast, the southern slope of Stromovka park is rather set aside from frequently used cycle routes, while a major entry point is located in the southeast of the park where no steep gradients can be found.

In contrast with the greenways, a general distribution of cycle routes across the parks is multidirectional. The waterfronts of Vltava in both parks are represented by unsegregated segments of A1 cycle route, but the difference in the motor traffic load there is significant. The part of A1 in Stromovka consists of a relatively calm road with a little share of through traffic, while the street by Letná is one of the busiest few lane roads in the city center.

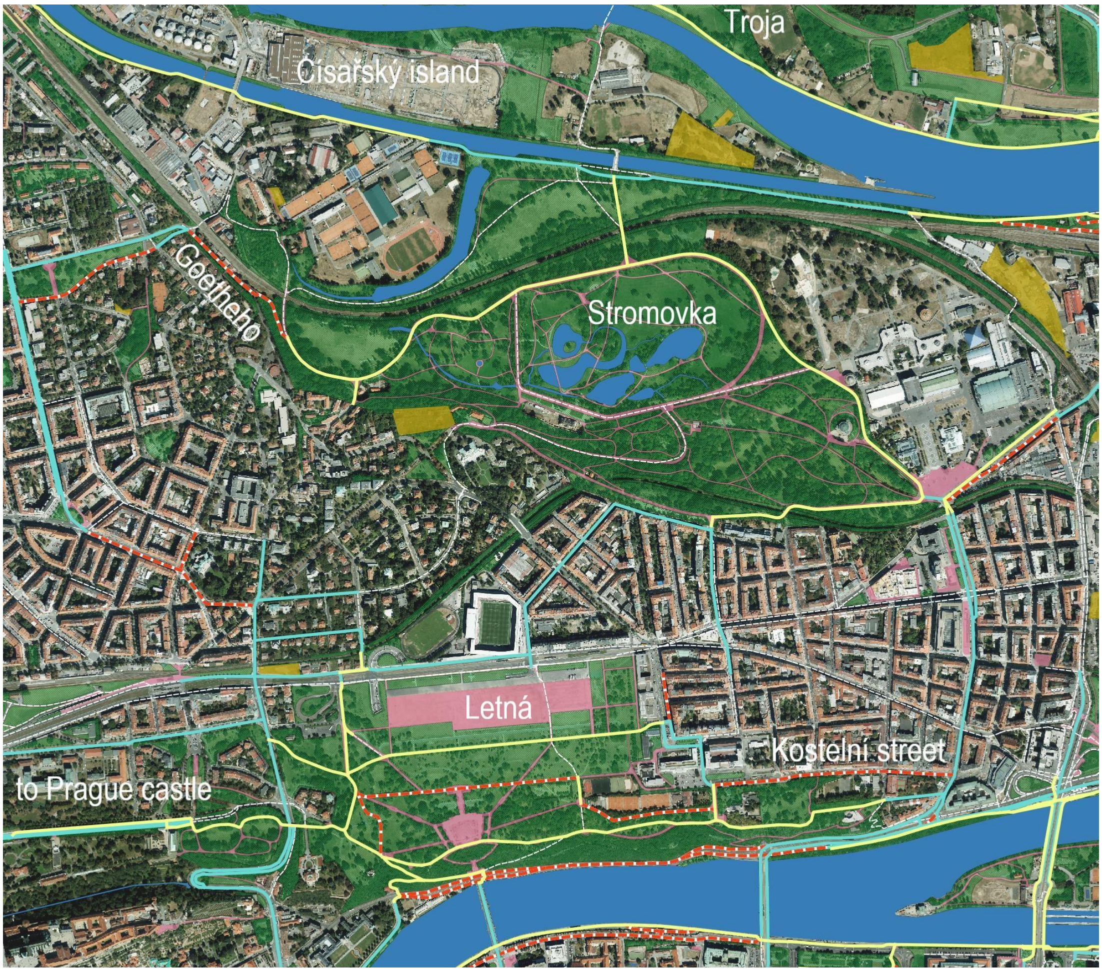


Figure 6.10 Stromovka and Letná parks and distribution of frequently used cycle routes

Due to an absence of bike counters in both parks it is difficult to estimate what are the shares of utility trips and recreational rides. The weekdays:weekends ratio of the bike counter installed at the very north of Stromovka at the *Císařský island* (17) has been identified as 49:51. Nonetheless, these numbers can not be stated as representative as in 2019 the only way to get to the right bank of the river from the island had been a ferry ride. The reconstructed Troja bridge for non-motorized users opened in October 2020, and today it is a part of the most direct connection between Troja district in the northern part of the city and center. Considering the intensity of use detected at the *'Povltavská'* (5) bike counter that has a 55% share of weekends in daily average rides it is decent to acknowledge that the number of rides this connection will rise up significantly, particularly on weekends (Table 5.1.5). The data from the bike counter that can be observed after November 2020 show that this segment of a bikeway system ultimately will become one of the busiest routes in Prague in 2021. The only gap in designated bikeways in Stromovka has been identified in a shortcut via Goetheho street in the northwest of park, which many cyclists use instead of curving through the other side of a railroad (Figure 6.10).

The Letná park also accommodates some of the essential cycle routes that connect the city center with the Hradčany neighborhood, Prague castle, and other districts. According to the system of cycle routes, these bikeways are predominantly unmarked and considered as recommended. Besides the above-mentioned southern steep slope that is actively used by cyclists as a shortcut, the eastern part of the park has a smoother gradient, which many cyclists use for a curve. One major gap identified in that part of the green area is related to the on-road segment in the Kostelní street, which is often used for an ascent due to a lesser gradient and perhaps a better road surface for motor traffic.

Both parks provide a space for safe segregated paths for non-motorized users that are frequently used as mixed-use paths. Some conflict zones appear in the section of the A310 cycle route in Stromovka that links the southeast of the park with its north. In the periods of good weather this part of the park is intensively used by pedestrians, joggers, inline skaters, and other users along with the cyclists, hence the accidents between them might occur. Considering the increasing popularity of this route among cyclists after the opening of Troja bridge, the creation of the exclusive bike path or other physical attributes of a separated lane might soon become a matter of safety of park visitors and a challenge for landscape planners.

An example of a long bike path with a separated lane for cyclists is presented in the Ladronka park (Figure 4.1). Similarly to Stromovka and Letná the park is formed by a vast flat area located to the west from the city center. Ladronka accommodates the primarily used cycle route (Appendix 3) labeled as 'Břevnov-Letná', which is a part of the A140 bikeway. Unlike the Stromovka and Letná parks, the terrain and configuration of Ladronka green space restrains the possibilities of multidirectional use for cycling, so the area is used as a busy bidirectional bike route. On a city scale the park plays a role of a transit space for cyclists who ride between multiple neighborhoods in the western part of the city (Břevnov, Řepy, etc.) and center (Figure 6.11). One of the main drawbacks creating a limitation for use in cycling and improved linkage with surrounding landscapes is represented by steep slopes that fringe the park from its southern and eastern sides (Appendix 5). The connection of the route with the city center is restrained by a steep gradient at the Petřin hill. One of the options for cyclists to climb this incline is represented by the Petřin funicular, which can possibly be better integrated into the system of cycle routes.

Figure 6.11 Ladronka park and the A140 cycle route with a separate bike path

One more green space that can be counted as a green patch in terms of urban landscape mosaics has been mentioned above as a part of a greenway along the Kunratický stream. The Kunratický forest is used by cyclists in multiple directions that are connected in the northwestern tip of the forest where they form a beginning of the separate A22 cycle path along the stream (Figure 6.3).

Thus, it is evident that not only greenways allocated along the water streams or their watersheds and valleys are important transit elements of the cycle routes network, but also large green spaces with flat terrain that accommodate major bikeways. Some green spaces as Stromovka and Letná might function as intersections of different routes oriented towards multiple directions. Some, as Ladronka, are accommodating bidirectional transit cycle highways, and some, as Kunratický forest, might constitute a space that assembles different bike routes and functions in symbiosis with a green corridor.

6.3.4 The mosaics of smaller green spaces

As mentioned before, based on the configuration and structure of green areas of Prague it is possible to categorize them in terms of landscape mosaics concept, which is based on morphology, functions, and scales of landscape elements. The examples of green spaces discussed above intend to show how types of Prague green areas can be categorized as urban corridors or patches. Besides given examples, some other levels of urban green infrastructure can be determined and evaluated from the perspective of their structure and functions, particularly in cycling network development.

For instance, the category of ‘urban matrix’ determined by Ahern (2007) can be applied to residential neighborhoods that incorporate calm residential streets with road verges, tree rows along the streets and small recreation grounds. This can also be relevant in assessment of mixed-use districts. Nonetheless, the evaluation of this category of green infrastructure and its role and perspectives in the development of safe cycle routes requires research at both local and city scales. In Prague, the examples of neighborhood matrices with a developed network of segregated cycle routes can be found in, for instance, Letnany and Stodůlky neighborhoods. Both examples however have some mistakes in planning and technical solutions used in implementation of cycle routes. Nonetheless, an evaluation of intensity of their use and identification of the gaps can help prevent the occurrence of such mistakes in other neighborhoods in the future.

The matrices of green infrastructure in the city center and mixed-use districts also incorporate small parks and recreation grounds that can be used in cycling network planning. As these ‘sites’ are often significantly smaller than urban green patches, their functionality in terms of cycle routes is often limited. Nonetheless, some sites like this can be often identified along the A1 and A2 cycle routes. For instance, as can be seen from the bike counters data, the *Kampa* (15) park situated at the A1 route is used by 486 cyclists on a daily average with a 68% share of weekdays in weekdays:weekends ratio. Many more green sites in the city center can be evaluated and improved in terms of creation of safe cycling infrastructure. Among examples are Charles square (*Karlovo náměstí*), Vrchlického gardens in front of the main train station, Čelakovského gardens around the building of the National Museum, and many more. The evaluation and identification of the role and possibilities of use of smaller green zones in the city center for non-motorized transport modes can be one of the important challenges that urban planners would face in Prague in the near future as the popularity of short-length rides rapidly grows in the era of wide accessibility of shared non-motorized modes of transport and social distancing. Considering the smaller areas of green sites in the city center in comparison to the examples of recreational parks and urban forests, it is fair to acknowledge that possibilities of their use for creation of segregated paths for non-motorized transportation are very limited. Instead, these areas can be used as hubs for other attributes of cycling infrastructure such as, for instance, parkings for bicycles and other modes of transport.

The evaluation of these green spaces that can be determined as ‘sites’ (Benedict & McMahon, 2006) or ‘matrices’ (Ahern, 2007) would require a closer scale of assessment than used in this present work. Also, as stated in Chapter 6.2 the lack of relevant and representative data is evident in terms of cycling intensity in the city center and neighborhoods. Green infrastructure is not limited by greenways or large recreational parks and it encompasses the system of various types of green areas in their different forms and shapes the qualities of which can often be used in the development of safe and segregated cycle routes. As seen from analysis presented in the present thesis, mixed-use and bike paths that involve exclusively non-motorized users often become a natural part of the green environment in an urban context.

7. Conclusion

A comparison of green infrastructure distribution and arrangement of frequently used cycle routes indicates a correlation between two systems. It is evident that large publicly accessible green spaces often provide a room for placement of segregated cycling infrastructure. These areas can not be underestimated in terms of their role in Prague urban cycling, as intensity of their use often corresponds to the level of primary cycle routes.

Based on the mosaics model from landscape ecology a few categories of urban green spaces can be determined according to their spatial configuration and functions in terms of distribution of cycle routes. There are greenways with segregated cycling infrastructure and former railroads transformed or planned to be converted into paths for non-motorized users that can be classified as urban green corridors as regards their morphology and spatial distribution of elements related to social activities. It is gauged that these green spaces are common to use by cyclists for both 'utility' and recreational rides. The role of these corridors is essential in terms of providing safe bidirectional connection between the city center and residential areas.

Nonetheless, it is illustrated that many bikeways associated with green corridors are lacking linkages with surrounding landscapes and neighborhoods or having gaps in designated routes due to either faults in applied technical solutions for hard infrastructure or complex topography with steep gradients along the greenway. Also, the connectivity between particular greenways is often low and fractured as no continuous and segregated cycle routes between them are presented. For instance, a good example of lacking linkage between greenways mentioned in the study illustrates an absence of connection between the A25 Vítkov bike path and A26 Rokytka greenway.

The terrain of Prague characterized by a wide distribution of steep slopes is one of the strong limitations for cycling, particularly associated with green spaces as almost 50% of their area lies on the slopes with over 7% gradients. From this perspective the value of in-roadway cycle routes and rail-trail bikeways increases due to lower gradients along these segments of transport infrastructure. This can also be proved by distribution of gaps in designated bikeways, which often correlate with on-road sections taken instead of segregated cycle routes that hold steeper gradients and worse quality of road surface. A necessity of the presence of safe cycling infrastructure along such sections of roads with motor traffic should not be neglected either. Properly designed bike lanes along some streets in Prague show a high intensity of their use by cyclists and often correspond with frequently used cycle routes. Nevertheless, the creation of bike lanes that can be considered safe and pleasant to ride by often requires significant transformations of the streetscape, which might lead to such consequences as elimination or decreased number of parking lots for cars. This, however, is an essential step if the city aims to become more sustainable providing a wider range of possibilities to deliver cultural ecosystem services to its citizens through the appearance of green transport infrastructure at the street scale.

Green patches, or green infrastructure hubs, are another determined element of urban green spaces in terms of their structure and functions. Notable examples of areas that fall under this category represented by Stromovka and Letná parks are discussed in the present work. Their structure allows to create a wider network of cycle routes oriented in multiple directions that connect different neighborhoods within themselves and with the city center. Also, the example of Kunratický forest shows that the interconnection of a green patch with a green corridor can increase functionality of green infrastructure in terms of distribution and use of non-motorized paths.

From the analysis of distribution of bikeways it is also evident that the Vltava river banks create a backbone of the whole network of cycle routes. A comparison of data from bike counters installed on different sides of the river at A1 and A2 cycle routes shows how different the intensity of use of bikeways can be when segregation of bikeways from motor traffic is not presented or does not occur in a consistent and uninterrupted manner.

An approach of cycling analysis that involved the bike counters data processing has illustrated how valuable a fixed and steady survey can be in terms of evaluation of cycle routes and intensity of their use in the course of a particular period of time. The weekdays:weekends ratio of rides gauged for each bike counter has helped quantify a load of cycling infrastructure in different locations and classify them with respect to the parts of a week when they are used more intensively, which is helpful for comprehension of the patterns of use of cycle routes in terms of purposes, particularly commuting and recreation.

It is evident that combination of different data sources helps evaluate the intensity and distribution of cycle routes more effectively allowing to implement comprehensive analysis of bike infrastructure efficiency and plan further development of cycle routes with the focus on their connectivity, consistency, and integrity with green infrastructure. Cycling population is a function of cycling infrastructure, and the proper design and planning of riding conditions are essential tools in making the environment safe and pleasant for its users.

8. References

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