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The Impact of Traffic Infrastructure, Environment, and User Behavior on Urban Bicycle Use: A Literature Review

Trafik altyapısı,çevre ve kullanıcı davranışının kentsel bisiklet kullanımına etkisine ilişkin literatür araştırması

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Abstract

Promoting bicycle use fosters health, orderliness, and improved transportation conditions. As a key component of active mobility, the global rise in bicycle usage reflects its growing importance. In developed cities, the use of conventional and e-bikes has increased, with cycling rates surpassing 7%. Despite the limited use in different cities, efforts to enhance bicycle usage are ongoing, although hindered by traffic safety issues and infrastructure deficiencies. This article conducts a detailed literature review to identify the necessary steps for increasing the share of bicycles in urban transportation. The review explores the impact of traffic infrastructure, environmental factors, and user behavior on urban bicycle use. Since the 1970s, these topics have been examined through various methods worldwide. This study reviews 95 articles published between 2010 and 2023, presenting a multifaceted analysis encompassing bicycle infrastructure, user behavior, and environmental factors affecting cycling. Key findings highlight the importance of well-planned bicycle infrastructure in enhancing safety and reducing traffic stress. Segregated bicycle lanes, effective intersection designs, and comprehensive cycling networks are crucial for promoting urban bicycle use. Environmental factors such as noise and air pollution, weather conditions, and urban design significantly influence cycling behavior. The review reveals that cities with robust cycling infrastructures and supportive policies, such as Copenhagen and Amsterdam, exhibit higher bicycle usage rates and improved urban mobility. Conversely, cities with inadequate infrastructure face challenges integrating bicycles as a viable transportation mode. The study suggests that adopting best practices from leading cycling cities and addressing local challenges can significantly enhance urban cycling. By providing a comprehensive overview of global research on urban bicycle use, this study aims to guide urban planners, policymakers, and researchers in developing effective strategies for promoting cycling as a sustainable and healthy transportation alternative. The insights gained can contribute to creating safer, more efficient, and environmentally friendly urban transport systems. This approach is vital for increasing bicycle usage and ensuring safe cycling practices, ultimately contributing to sustainable urban development.

Keywords: Cycleability, Cycling Safety, Traffic Stress Level, Cycling Infrastructure

Öz

Bisiklet kullanımını teşvik etmek, sağlık, düzen ve daha iyi ulaşım koşullarını destekler. Aktif hareketliliğin önemli bir bileşeni olarak, bisiklet kullanımındaki küresel artış, bisikletin artan önemini yansıtmaktadır. Gelişmiş şehirlerde, konvansiyonel ve e-bisiklet kullanımı artmış ve bisiklete binme oranları %7'nin üzerine çıkmıştır. Farklı şehirlerdeki sınırlı kullanıma rağmen, bisiklet kullanımını artırmaya yönelik çabalar devam etmektedir, ancak trafik güvenliği sorunları ve altyapı eksiklikleri bu süreci engellemektedir. Bu makale, kentsel ulaşımda bisikletin payını artırmak için gerekli adımları belirlemek amacıyla detaylı bir literatür incelemesi yapmaktadır. İnceleme, kentsel bisiklet kullanımına trafik altyapısı, çevresel faktörler ve kullanıcı davranışının etkisini araştırmaktadır. 1970'lerden bu yana, bu konular dünya genelinde çeşitli yöntemlerle incelenmiştir. Bu çalışma, 2010-2023 yılları arasında yayınlanan 95 makaleyi inceleyerek, bisiklet altyapısı, kullanıcı davranışı ve bisiklet kullanımını etkileyen çevresel faktörleri kapsayan çok yönlü bir analiz sunmaktadır. Ana bulgular, iyi planlanmış bisiklet altyapısının güvenliği artırmada ve trafik stresini azaltmada önemini vurgulamaktadır. Ayrılmış bisiklet yolları, etkili kavşak tasarımları ve kapsamlı bisiklet ağları, kentsel bisiklet kullanımını teşvik etmek için kritik öneme sahiptir. Gürültü ve hava kirliliği, hava koşulları ve kentsel tasarım gibi çevresel faktörler, bisiklet davranışını önemli ölçüde etkiler. İnceleme, Kopenhag ve Amsterdam gibi güçlü bisiklet altyapısına ve destekleyici politikalara sahip şehirlerin, daha yüksek bisiklet kullanım oranları ve gelişmiş kentsel hareketlilik sergilediğini ortaya koymaktadır. Buna karşılık, yetersiz altyapıya sahip şehirler, bisikletleri uygulanabilir bir ulaşım modu olarak entegre etmede zorluklarla karşılaşmaktadır. Çalışma, önde gelen bisiklet şehirlerinden en iyi uygulamaların benimsenmesinin ve yerel zorlukların ele alınmasının, kentsel bisiklet kullanımını önemli ölçüde artırabileceğini önermektedir. Elde edilen bilgiler, daha güvenli, verimli ve çevre dostu kentsel ulaşım sistemleri yaratılmasına katkıda bulunabilir. Bu yaklaşım, bisiklet kullanımını artırmak ve güvenli bisiklet uygulamalarını sağlamak için hayati öneme sahiptir ve nihayetinde sürdürülebilir kentsel gelişime katkıda bulunur.

Anahtar kelimeler: Bisiklete binilebilirlilik, Bisiklet Güvenliği, Trafik Stres Seviyesi, Bisiklet Altyapısı

1 Introduction

In cities worldwide, the growing population has led to expansion and increased use of private vehicles for transportation. As urban traffic reaches capacity, cities are shifting towards new modes of transportation. Developed countries are investing in transportation infrastructure due to the negative impacts of vehicles in city centers, such as noise, carbon emissions, and psychological and sociological effects. This has led to the adoptingof more economical and healthy

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transportation modes, particularly in Northern European countries like Germany, Netherlands, Denmark, and Sweden, with a trend towards greener transportation such as bicycles, e-bikes, e-scooters, metro, and walking. The main goal is to create more livable and less stressful cities for the future. In recent years, active mobility, a part of sustainability, has become a focus in urban planning, especially in Europe.

Sustainable cities aim to create environmentally friendly and livable cities in the 2030s [1]. It focuses on maintaining long-term, balanced relationships between society and nature. Sustainability refers to the ability of a society, ecosystem, or any enduring system to continue functioning without interruption, deterioration, overuse, or excessive strain on essential resources. The idea of sustainable development was first introduced in the "Brundtland Report (1987)," which defines it as development that meets present needs without compromising the ability of future generations to meet their own needs[2]. Accelerated infrastructure and educational activities are essential to transition to sustainable and healthy transportation models. Different countries are at varying levels of development in this regard, with Asia focusing on two-wheeled vehicles, Europe including cars and electric vehicles, and America primarily centered around cars.

A bicycle is a vehicle that has benefits in many different areas, both on an individual scale and on a city scale. However, its use for transportation purposes is not sufficient in our country. For the bicycle, which is an effective tool for a healthier life with its physical and mental benefits, to be included in our daily lives, we need to ensure that bicycles become a mode of transportation in cities. In order to make bicycles more visible in traffic, bicycle transportation infrastructure should be designed as a building block within the scope of transportation master plans in cities. At the same time, bicycle transportation should be supported through awareness and incentive mechanisms. The main benefit of the bicycle is that it is a free form of transportation. The vehicle, which has been able to move forward without the need for any fuel or electricity since the day it was invented, has continued its development after the 2000s, especially to improve people's social and cultural aspects.

The use of bicycles is increasing in Turkey, particularly in urban areas where they are mainly chosen for recreational purposes. However, unlike in European countries where bicycles are a primary mode of transportation and efforts are made to increase their usage annually, Turkey still needs to catch up. The use of bicycles depends largely on regulations and infrastructure. Despite the increasing construction of bicycle lanes in major Turkish cities, these often need to be planned and implemented as part of a comprehensive transportation system. In addition, the need for well-designed bicycle networks, adequate infrastructure, and proper cycling regulations result in low bicycle use. Figure 1 illustrates the current state of bicycle use and infrastructure in Turkey. While Turkey reflects the global trend towards increased bicycle use, this progress is largely unplanned in many cities.Some initiatives overlook city integrity, infrastructure, and the role of bicycles in transportation, opting instead for popularist approaches. These approaches often lead to uncontrolled situations and increased bicycle traffic accidents, discouraging people from using bicycles.

The study investigates the impact of the current infrastructure in Turkey on cyclists by analyzing global literature. It focuses on fundamental concepts related to urban cycling, such as traffic stress levels, bicycle infrastructure and safety, experimental bicycle studies, noise and air pollution, bicycle use at intersections, weather conditions, lateral crossing distances, and cyclist behavior. A total of 95 research articles and literature reviews from the https://www.sciencedirect.com platform from 2010 to 2023 were examined. This study aims to help academics and infrastructure designers determine the infrastructure factors that should be considered to promote safer, higher quality, and widespread bicycle use in urban areas.

With its growing population, national income, and increasing population, national income, and urbanization rate, Turkey aims to reach the bicycle use rates of developed countries by integrating bicycle use strategies with good infrastructure and education studies as an alternative to automobiles. However, rugged terrain, traffic irregularities, and weather conditions present negative parameters for Turkey. This study emphasizes the benefits of implementing appropriate methods in areas suitable for bicycle use. The primary goal is to create a healthy bicycle infrastructure, reduce private vehicle density, and establish a sustainable transportation system by integrating a bicycle usage system with public transportation. In this respect, it is vital to determine the correct infrastructure parameters and design accordingly to develop an approach that will increase bicycle usage rates to 5-7% in cities. In addition, this study enables cyclists, academics, and bicycle infrastructure designers to address existing or planned bicycle infrastructure in urban areas more effectively.

2 The State of Bicycle Infrastructure in Turkey and Europe

Since the bicycle usage rate in Turkey aims to reach the usage rates of developed countries, any research and development regarding bicycles is very valuable.In Turkey, the bicycle network is mostly used in recreational areas outside of cities, with minimal use for transportation. However, investing in bicycle infrastructure in large cities, towns, and districts that meet specific slope and road width criteria is suitable as a developing country. Cities such as Istanbul, Sakarya, Eskişehir, Antalya, and Konya actively promote bicycle use through local and civil society initiatives. The Ministry of Environment, Urbanization, and Climate Change has announced plans to construct 4,775 km of bicycle paths across the country by 2023. Efforts to increase bicycle paths in all 81 provinces began in 2018, with 102 km of bicycle paths completed in Afyonkarahisar, Amasya, Ankara, Antalya, Aydın, Çankırı, Erzurum, Gaziantep, Istanbul, Kahramanmaraş, Malatya, Rize, Sakarya, Trabzon, and Tunceli. The construction of 114 km of bicycle paths in provinces such as Batman, Bitlis, Çanakkale, Istanbul, and Konya is ongoing. Notably, out of the 4,775 km of bicycle paths planned to be completed by 2023, only 216 km have been implemented [3].

There are some current articles on bicycles in Turkey. Among these, Saplıoğlu and Aydın [4] conducted route analyses by examining parameters such as traffic capacity, bicycle parking, longitudinal slope of the road, etc., which may be effective in route selection in the case of integrated use of bicycles and public transport systems. Uz and Karaşahin [5] also conducted studies emphasizing the importance of separated bicycle paths regarding traffic infrastructure.Yılmaz and Gercek [6] evaluated the effect of non-motorized and public transportation integration on high-level mobility. The study addressed the role of bicycles in non-motorized transportation and their contributions to the sustainable travel goal. In the established model, data such as public transportation lines planned for 2023, transfer center points, passenger numbers at these points, and the reorganized bicycle network were used as a base for the map developed in the Geographic Information Systems (GIS) environment.

Eren and Uz [7] evaluate recent studies on station-based bike sharing in the literature and seek answers to two main research questions: First, how do weather conditions, built environment and land use, public transportation, socio-demographic characteristics, temporal factors, and safety affect bike sharing trip demand? Second, what are the most commonly used factors affecting trip demand in the literature? Pekdemir et al. [8] aimed to investigate travel purposes and travel situations in a small-scale moored bike-sharing system operating in Izmir, Turkey. A two-stage process was used to determine travel purposes: leisure cycling and transportation cycling. Dündar et al. [9] examined the seasonal bicycle usage numbers and the factors affecting this in 4 cities where one of Turkey's leading organizations in the micro-mobility field provides bicycle sharing service. With the developed model, they could estimate the number of trips in the cities where bicycle-sharing service is provided and the changes in these trips.

Turkey faces significant annual losses, both financial and moral, due to fatal and injury-causing traffic accidents. One of the most significant losses is the psychological impact on people, making them feel unsafe during transportation. Historically, Turkey's infrastructure design has focused on vehicle traffic for almost all cities. This approach has been applied across all regions, leading to negative effects for cities that are beginning to use bicycles or are already using them. The geometric concepts need to be adapted to accommodate bicycle use to ensure that cyclists can ride comfortably and safely. Thus, parameters such as intersections, road axes, pedestrian arrangements, speed regulations, and parking need to be reconsidered.

Globally, the bicycle has always maintained its popularity over time. It was first invented in the 1850s and was primarily used for recreation and transportation until the 1900s. However, bicycle usage rates declined with the invention of the car in the 1900s. Nonetheless, driven by its spirit of freedom, the bicycle saw a resurgence in the 1970s in countries like the Netherlands and Denmark due to factors such as the scarcity of petroleum products and global air pollution. This resurgence brought bicycle usage levels back to when it was first invented. [10].

Bicycles are integral to daily transportation in EU countries such as Denmark, the Netherlands, and Germany. Many European cities began investing in bicycle transportation infrastructure in the 1900s. Consequently, they have specific plans and goals for promoting bicycle transportation. These countries consistently implement supportive policies to popularize bicycle use and encourage environmentally friendly, active transportation modes [11].

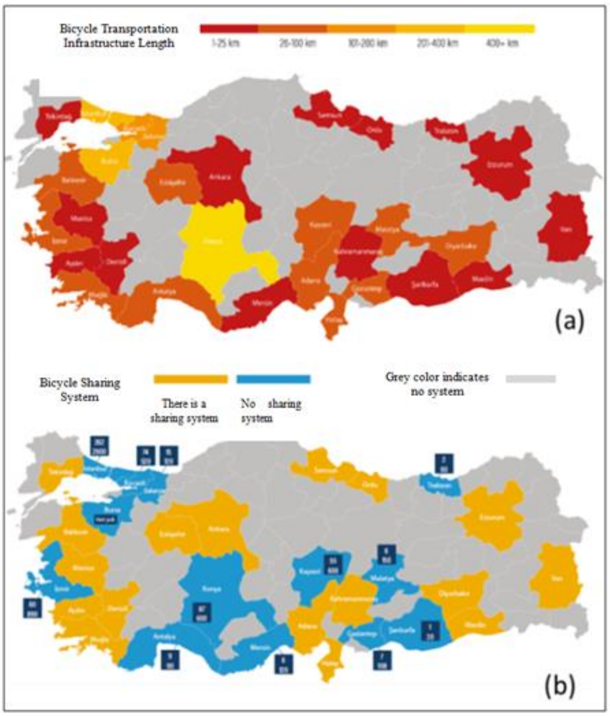


Figure 1. Bicycle infrastructure and shared bicycle situation in Turkey: (a) infrastructure lengths and b) bicycle sharing system distribution [12].

In Copenhagen, the capital of Denmark, the rate of bicycles being chosen among all transportation modes was calculated to be 49.1% in 2018. The extensive use of bicycles as a significant part of daily life can be attributed to the bicycle infrastructure that began construction in 1912 and the car-restricting policies implemented in 2017[13].

Another bicycle-friendly European city, Amsterdam, the capital of the Netherlands, had a bicycle usage rate of 36.2% among all transportation modes in 2017. In the city center, this rate reached 48%. The city's macrostructure is highly conducive to bicycle transportation infrastructure, with more than 750 km of bicycle paths resulting from infrastructure projects that began in 1970. In the German city of Bremen, the bicycle usage rate among all transportation modes was calculated to be 25.3% in 2019. With this rate and 674 km of dedicated bicycle paths, Bremen stands out as Germany's leading bicycle-friendly city. Following the widespread adoption of the bicycle street concept in Germany, Bremen implemented the bicycle zone program. This program allocated €2.4 million for planning and implementing bicycle-priority roads and networks, bicycle-friendly road surfaces, and bicycle parking facilities in the Weser Bicycle Region.[12].

Sweden, Finland, and France have also recently made significant infrastructure investments.Increased bicycle use creates better environmental living standards, helps reduce the spread of harmful greenhouse gases and carbon monoxide, and limits noise pollution. Therefore, countries are actively working to promote bicycle use, offering incentives for such initiatives. Additionally, they organize events to encourage people to use bicycles.

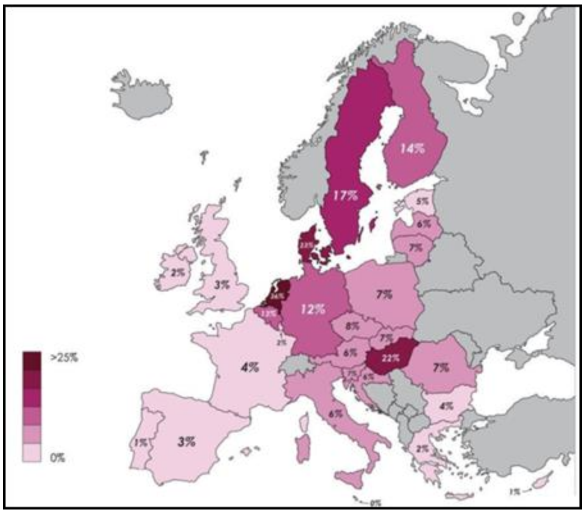


Figure 2. Percentage (%) use of bicycles in transportation in urope 2014 WRI [12].

3 Importance of Infrastructure for Bicycles

Bicycle usage varies from country to country. Most countries around the world use non-motorized vehicles[13]. Factors such as population density, taxes on vehicle sales, parking problems, and high taxes on vehicle fuels are policies that promote the inclusion of non-motorized vehicles in transportation planning. However, unlike high-cycling countries, low-cycling regions represent a greater diversity of geographical areas, world regions, and income levels. In most of these areas, bicycle-supportive infrastructure is rare. Policies to discourage car use are often lacking in countries like the USA and Australia. In many low- and middle-income countries, while land use is relatively less dependent on vehicles and vehicle ownership remains low, transportation policies are often car-centric, and traffic hazards are high [14].

In countries where bicycles are extensively used for transportation, various conceptual studies have been developed to increase further and ensure safe bicycle use. These methods involve assessing the impact of bicycles on vehicles and infrastructure. Notably, the United States has developed the Level of Traffic Stress (LTS) system, using the Dutch Bicycle Infrastructure Guide (CROW) as a reference, to make its roads more bicycle-friendly and improve existing routes[14]. This system has been adapted to different indices in some countries, such as Germany and Denmark [16].

Measuring the impact of infrastructure on cyclist safety is crucial. Bicycle usage in Turkey is increasing daily. Like global trends, the pandemic has accelerated the use of non-motorized vehicles in Turkey, evidenced by the rising number of bicycles and scooters in traffic. Understanding the levels of traffic impact on bicycle use is vital for developing and better evaluating Turkey's bicycle infrastructure.

Countries like Germany, Denmark, Japan, and the Netherlands are leading the world in achieving high levels of bicycle usage and positive gender and age representation. In these countries, infrastructure services such as protected bike lanes and secure parking facilities for cyclists are common. These measures contribute to reducing motorized traffic in residential areas, calming cities, and increasing the use of hybrid transportation systems.

Countries with low bicycle usage, such as Bogotá and Colombia, stand out as exemplary models. Supported by political and local administrations and advocacy groups, the enhancement of bicycle infrastructure in Bogotá has led to a significant increase in cycling levels [15]. Despite limited resources, in visionary projects, Bogotá has demonstrated remarkable success in promoting bicycle use in recent years. This success makes Bogotá a notable example for many developing cities aiming to improve their cycling infrastructure. As shown in Table 1, Bogota ranked 12th in the 2019 Copenhagenize Index, which measures and publishes cycling metrics in cities worldwide.

Table 1. Copenhagen Index ranking of cities between 2013-2019 [15].

Order	2015	Country	2017	Country	2019	Country
1	Copenhagen	Denmark	Copenhagen	Denmark	Copenhagen	Denmark
2	Amsterdam	Holland	Utrecht	Holland	Amsterdam	Holland
3	Utrecht	Holland	Amsterdam	Holland	Utrecht	Holland
4	Eindhoven	Holland	Strasbourg	France	Anvers	Belgium
5	Malmo	Sweden	Malmo	Sweden	Strasbourg	France
6	Nantes	France	Bordo	France	Bordo	France
7	Bordo	France	Anvers	Belgium	Oslo	Norway
8	Strasbourg	France	Ljubljana	Slovenia	Paris	France
9	Anvers	Belgium	Tokyo	Japan	Vienna	Austria
10	Sevilla	Spain	Berlin	Germany	Helsinki	Finland
11	Barcelona	Spain	Barcelona	Spain	Bremen	Germany
12	Ljubljana	Slovenia	Vienna	Australia	Bogota	Colombia
13	Dublin	Ireland	Paris	France	Barcelona	Spain
14	Buenos Aires	Argentina	Sevilla	Spain	Ljubljana	Slovenia
15	Berlin	Germany	Munich	Germany	Berlin	Germany
16	Minneapolis	Amerika	Nantes	France	Tokyo	Japan
17	Paris	France	Hamburg	Germany	Taipei	Taiwan
18	Hamburg	Germany	Helsinki	Finland	Montreal	Australia
19	Munich	Germany	Oslo	Norway	Vancouver	Canada
20	Montreal	Australia	Montreal	Australia	Hamburg	Germany

4 Literature Review of Infrastructure, Environmental, and Behavioral Factors

Understanding the future of a city and making the necessary decisions to ensure its healthy development is considered the most crucial step in urban planning. In this context, urban transportation planning is essential for the healthy growth of cities and the creation of sustainable spaces. Urban transportation planning not only organizes a city's traffic but also shapes the physical structures that form the architectural and social fabric of the city, along with the cultural activities that bring this structure to life.In recent years, bicycle usage in Turkey has gained momentum and has become a popular mode of behavior among people. A well-planned approach is necessary to effectively integrate bicycles into active mobility, which is comfortable, natural, and healthy. Historically, road infrastructure in Turkish cities was designed with automobiles in mind, and now it is being adapted to accommodate bicycles as the concept gains prominence. However, local administrations often face challenges in this regard. Well-designed infrastructure that considers the needs of cyclists is essential for promoting bicycle use.

These studies' general information and keywords are provided in Table 2, and their grouped forms according to the selected factors are presented in Table 3.

Table 2. Literature Studies and Keywords

No.	Study	Keywords	No.	Study	Keywords	No.	Study	Keywords
C1	Apasnore et al. (2016)	Bicycle infrastructure, Bikeability	C31	Gelb and Appricio (2022)	Air (NO2), Noise level	C61	Morrison et al. (2019)	Bike path, Spatial analysis
C2	Apparicio et al. (2016)	Cyclist, Noise, Air pollution	C32	Gitelman et al. (2022)	Urban intersections, User behavior, E-bike	C62	Ng et al. (2017)	Bicycle infrastructure, Safety, Intersection
C3	Autelitano and Giulani (2021)	Road Engineering, Bicycle Infrastructure	C33	Gitelman et al. (2020)	Urban Intersections, User Behavior	C63	Nazemi et al. (2021)	Perceived safety level of cycling
C4	Bai and Sze (2020)	E-bike, Signalized intersection, Bicycle safety	C34	Goel et al. (2021)	Cyclist Behavior, Age, Gender	C64	Hull and O'Holleran (2014)	Bicycle infrastructure design, Perception of safety
C5	Bas et al. (2023)	Traffic stress level, Planning	C35	Gomez and Castro (2020)	Urban intersections, Road safety, Visibility	C65	Olmos et al. (2020)	Bicycle infrastructure planning, Mobile phone data
C6	Beck et al. (2019)	Passing distance, Road infrastructure, Bicycle safety	C36	Guo et al. (2023)	Cycling behavior, Eye tracking	C66	Querg et al. (2021)	Bicycle infrastructure, Traffic stress and index
C7	Beck et al. (2021)	Passing distance, User behavior	C37	Hagen and Ralph (2019)	Traffic stress level	C67	Padillo et al. (2021)	Traffic safety, Bike path
C8	Begou et al. (2020)	Noise pollution, Road traffic noise	C38	Harkey et al. (1998)	Traffic stress	C68	Rodrigues et al. (2022)	Traffic Stress Level, Physiological Stress
C9	Boettge et al. (2017)	Bicycle infrastructure, Urban planning	C39	Saplıoğlu and Aydın (2018)	Bicycle safety	C69	Rubie et al. (2020)	Lateral passing distance, Overtaking, Cyclist safety
C10	Bearn et al. (2018)	Traffic stress level	C40	Ising et al. (2004)	Noise, User stress	C70	Rubie et al. (2023)	Lateral passing distance, User attitude and behavior
C11	Bergström and Magnusson (2003)	Bike Paths, Winter Maintenance	C41	Imani et al. (2019)	Traffic stress level	C71	Scoot et al. (2023)	Intersection improvement, Simulator, Safety
C12	Boisjoly et al. (2019)	Bike Paths, Travel behavior	C42	Janssen et al. (2018)	Behavior, Sidewalk infrastructure	C72	Singleton and Paudel (2023)	Modern Roundabout, Bicycle Safety
C13	Bosen et al. (2023)	Bicycle Mobility, Risk perception	C43	Kaynak 2 (2019)	Traffic Stress Level, Bicycle Index	C73	Singleton and Paudel (2021)	Modern roundabout, User behavior
C14	Cabral et al. (2019)	Traffic stress level	C44	Kent and Karner (2018)	Bikeability, Traffic stress level	C74	Soni et al. (2022)	Road traffic noise, Environmental noise
C15	Cabral and Kim (2022)	Traffic stress level, Bicycle comfort level	C45	Kircher and Ahlström (2020)	User behavior, Intersections	C75	Sorton and Walsh (1994)	Traffic stress
C16	Cai and Pei (2021)	Cold climate cities, Cyclists	C46	Uz and Karaşahin (2004)	Bicycle infrastructure	C76	Stülpnagel and Binning (2022)	Bicycle infrastructure, Subjective safety
C17	Can et al. (2020)	Noise reduction, Urban noise future	C47	Koh and Wong (2013)	Bikeability, Cyclist	C77	Stülpnagel et al. (2022)	Passing distance, Bicycle infrastructure
C18	Caviedes and Figliozzi (2018)	Stress, Traffic	C48	Kovacsova et al. (2020)	Cyclist awareness, E-Bike	C78	Wang et al. (2020)	Traffic stress level
C19	Deliali et al. (2021)	Protected intersection, Protected lane, Bicycle Simulator	C49	Landis et al. (1997)	Traffic stress level	C79	Yılmaz and Gerçek (2014)	Bikeability
C20	DiGioia et al. (2017)	Cyclist safety, Data collection	C50	Lee et al. (2020)	Bicycle safety, Bicycle behavior, Equipped bike	C80	Werner et al. (2019)	Bikeability; Stress feeling; Infrastructure assessment
C21	Dozza et al. (2022)	Traffic safety, E-bike, Equipped bike	C51	Lierop et al. (2020)	Bike Path Markings, E-bike	C81	Walker (2007)	Overtaking, Gender, Bicycle Helmet
C22	Feng et al. (2018)	Passing distance, User behavior	C52	Liu and Suzuki (2019)	E-Bike, Equipped bike, Energy expenditure	C82	Werneke et al. (2015)	Bicycle safety, Cyclist behavior, Data collection
C23	Fenre and Paste (2021)	Winter Cycling, Winter maintenance	C53	Lowry et al. (2016)	Traffic stress level, Accessibility	C83	Eren and Uz (2020)	Bike Sharing
C24	Fernandez et al. (2022)	Overtaking maneuver	C54	Lu et al. (2019)	Traffic noise, Road characteristics, Traffic flow	C84	Wysling and Purves (2022)	Bicycle infrastructure, Bikeability
C25	Fitch et al. (2020)	Travel Behavior, Stress, Equipped bike	C55	Mackenzie et al. (2021)	Passing distance, Safety	C85	Valenzuela et al. (2022)	Road slope, Uphill cycling
C26	Fournier et al. (2020)	Bicycle infrastructure, Bicycle safety	C56	Madsen and Lahrmann (2017)	Road design, Signalized intersection	C86	Zangenehpour et al. (2016)	Cyclist safety, Intersections
C27	Furth et al. (2023)	Bicycle infrastructure, Slope	C57	Makarova et al. (2020)	Bicycle infrastructure, Decision support system	C87	Zhao et al. (2023)	Perception, Sound measurement
C28	Gao et al. (2018)	Vibration Perception	C58	Marchiori et al. (2018)	Bicycle equipment	C88	Zhao et al. (2018)	CROW principles, Planning
C29	Gadsby et al. (2021)	Equipped bike	C59	Mekuria et al. (2012)	Traffic stress level	C89	Zhu and Zhu (2019)	Bicycle comfort index, Equipped bike
C30	Geelong Bike Plan (1979)	Traffic stress	C60	Mohammadi et al. (2023)	Cyclist interaction, Intersections	C90	Pekdemir et al. (2024)	Bicycle infrastructure

Table3.Infrastructure and Environmental Factors Affecting Bicycle Use

Factor	Number of Affected Studies	Study No.
Infrastructure		
Traffic Infrastructure and Safety	42	C1-C4, C6, C9, C12-C13, C15-C16, C19-C21, C23, C26-C27, C35,C39,C42,C46-C47, C50-C51, C54-C57, C61-C64, C66-C67, C69, C71-C72, C76-C77, C80, C82-C86, C88
Intersections	12	C4, C19, C32-C33, C35, C45, C56, C60, C62, C71-C73, C86
Bike Sharing	1	C83
Passing Distance	10	C1, C6-C7, C22, C24, C55, C69-C70, C77, C81
Traffic Stress	19	C5, C10, C14-C15, C18, C30, C37-C38, C41, C43-C44, C49, C53, C59, C66, C68, C75, C78, C89
User		
User Stress	5	C25, C40, C52, C68, C80
User Behavior	18	C7, C12, C22, C25, C32-C35, C42, C45, C48, C50, C60, C70, C73, C79, C81-C82
E-Bike	6	C4, C21, C32, C48, C51-C52
Bicycle Simulator	2	C19, C71
Experimental Bicycle	13	C13, C20, C21, C25, C28-C29, C50, C52, C54, C58, C-79,C81-C82, C89
Environmental		
Noise, Air Pollution	7	C2, C8, C17, C31, C40, C74, C87
Weather Conditions	3	C11, C16, C23

4.1 Infrastructure Factors

4.1.1 Traffic Infrastructure and Safety

Traffic infrastructure is one of the most significant physical factors affecting cyclists. The infrastructural safety of cyclists positively impacts bicycle usage. Here, 19 articles directly related to infrastructure and bicycle studies were reviewed. The reviewed articles included studies on the safety-infrastructure relationship, types of bicycle infrastructure (segregated bike lanes, bike lanes, mixed traffic), sidewalks, slopes, and bicycle markings.

In these studies, Padillo et al. [16] proposed a bicycle lane safety level audit tool to support decision-making regarding opportunities to improve safety. The study showed that 40% of the impact weight on safety in bicycle lanes is concentrated in 20% of certain features. User behaviors, the geometry of bicycle lane design, relative speeds between vehicles, and existing obstacles in bike lanes were important factors in achieving significant safety gains.Koh and Wong [17] used a two-pronged approach to evaluate which infrastructural compatibility factors influence the willingness to choose a desired bike path. An intersection perception survey and bikeability audits were conducted to evaluate various factors. The study found that safety was the most critical factor for cyclists. O'Holleran and Hull [18] emphasized that busy roads pose safety vulnerabilities. Nazemi et al. [19] found that the traffic volume passing through a lane affects bicycle safety.

Boettge et al. [20] considered road functional classification and the number of lanes. They found that a higher number of lanes resulted in more stress. Zhao et al. [21] compared the strengths and weaknesses of bicycle infrastructure planning in Copenhagen, which has a robust bicycle infrastructure, and Beijing, which has less bicycle experience. Valenzuela et al. [22] collected power output data from professional cyclists during both training sessions and competitions over ten years (2013-2022). They found that participants reached maximum average power on slopes averaging 6.0-7.3%, regardless of effort durations or cyclist typologies.

Furth et al. [23] used GPS data from approximately 73,000 bicycle trips in Zurich and found that a 1% increase in maximum slope was equivalent to adding 9% more to the road network length. Makarova et al. [24] considered both infrastructure and administrative decisions, identifying areas for improving bicycle infrastructure safety by examining current positive global practices. DiGioia et al. [25] highlighted data needs and critically reviewedcurrent research on bicycle infrastructure improvements. They reviewed 22 safety literature studies on bicycle improvements, examining findings, study methodologies, and data sources used.

Lierop et al. [26] conducted one-on-one interviews with twelve e-bike users unfamiliar with the bike path in Tilburg and Waalwijk, Netherlands, to evaluate their experiences with traditional signage before changes were made to the wayfinding system on the bicycle highway in 2018. The evaluations showed that new changes in the location, size, and clarity of signage improved cyclists' overall experiences and perceptions of the built environment.Stülpnagel and Binnig [27] presented subjects with simulation scenarios of narrow streets with low traffic, narrow streets with heavy traffic, and wide streets with heavy traffic. They found that roads with less width and lower traffic volumes were considered safer for cycling.

Morrisson et al. [28] identified the road bicycle lanes that significantly reduce bicycle accidents, considering certain road characteristics. In all these environments, only dedicated bicycle lanes were associated with a decreased likelihood of accidents.

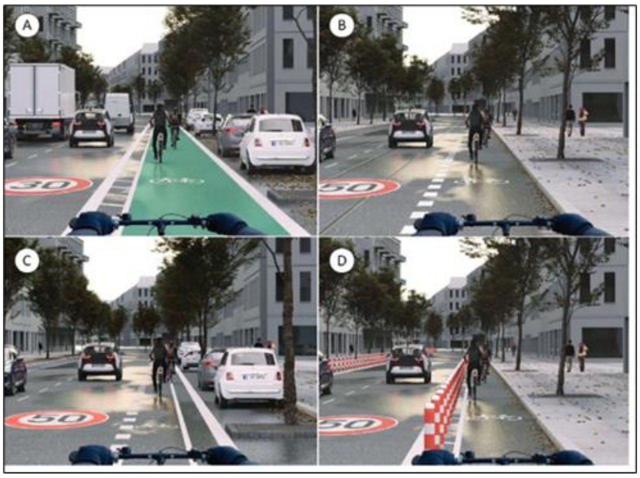


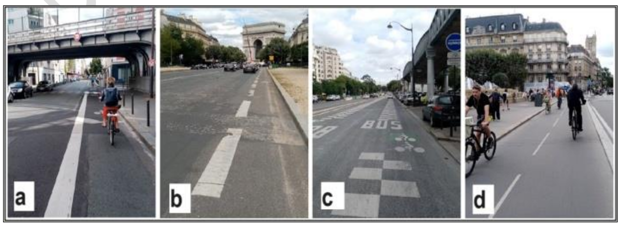
Figure 3. Illustration of the images used as simulation in the survey. A:Speed limit: 30 km/h; street type: wide street with high traffic. B:Speed limit: 50 km/h; street type: small street with tram rails. C:speed limit: 50 km/h; street type: small street with little traffic. D: speed limit: 50 km/h; street type: small street with little traffic [27].

Autelitano and Giulani [29] conducted a comprehensive literature review of over 50 scientific articles and more than 80 official designs, guidelines, and standards worldwide. Their study provided a guided overview of the latest technology related to the use of color in bicycle facilities.Wysling and Purves [30] found that cyclists were willing to deviate from their routes by 36% to avoid streets with over 10,000 vehicles per day, highlighting the problem of roads with high vehicle volumes.Olmos et al. [31] monitored bicycle trips by combining mobile phone data and GPS traces from a smartphone app for cyclists.

Figure 4. Common types of bicycle infrastructure in the city of Paris: (a), Bicycle use on one-way streets (b), Marked bicycle lanes; (c), Shared bus lanes (d), Physically separated bicycle lanes [31].

4.1.2 Traffic and User Stress Studies

One of the key areas of bicycle infrastructure studies is related to traffic stress levels. The concept of traffic stress levels was introduced in the 1970s with the Geelong Bike Plan in Australia and remains valid today through numerous field studies examining different aspects of infrastructure parameters. Nineteen articles focusing on stress as their main subject were reviewed. These articles covered topics such as traffic infrastructure-stress factors, the bicycle index, physiological stress, and bicycle network connectivity assessment. The conditions created by infrastructure and other factors affecting cycling and usage are components of stress analysis, aiming to ensure safer travel for cyclists in cities.



From the reviewed articles, the Geelong Bike Plan in 1978 recognized the importance of understanding the cyclist's perspective on infrastructure and was the first to incorporate this into the concept known as the bicycle stress level. In a study by Sorton and Walsh [32], the concept of bicycle stress level was among the earliest used. The study attempted to relate cyclists' perspectives on road types to specific geometric and traffic conditions. The authors created a stress level rating from 1 to 5 by accounting for traffic variables such as volume, speed, and curb width, thereby determining bicycle stress levels.

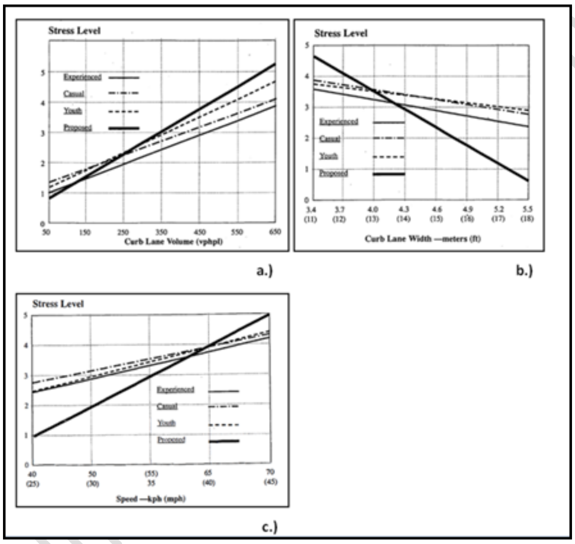


Figure 5. Stress Level study results: (a) Curbside lane volume-Stress level relationship (b) Curbside lane width-Stress level relationship (c) Speed-stress level relationship [32].

Landis et al. [33] developed the Bicycle Level of Service (BLOS) concept. This statistical model measures the suitability of roads and the quality of service provided to cyclists traveling on the road networks of urbanized areas in the United States. The developed model is shown below.

$$BLOS = a1\ln(Vol15/L)a2\ln(SDPp(1 + \%HV)) + a3\ln(COM15xNCA) + a4(PC5) - 2 + a5(We)2 + C \quad (1)$$

Where;

BLOS =Perceived hazard of the shared roadway environment,
Vol15 = Directional traffic volume in 15 minutes,

L = Total number of through lanes,

SPDp = Posted speed limit,

V = Percentage of heavy vehicles,

COM15 = Trip generation intensity of land use adjacent to the road segment,

NCA = Effective frequency of uncontrolled vehicular access points per mile,

PC5 = FHWA's 5-point pavement surface condition rating,

We = Average effective width of the outside through lane.

Harkey et al. [33] developed the Bicycle Compatibility Index (BCI), which assesses how well bicycles and motor vehicles coexist with other factors in traffic. The model is shown below:

$$\begin{aligned} BCI = 3.67 - 0.966BL - 0.41BLW + 0.498CLW \\ + 0.002CLV + 0.0004OLV + 0.22SPD \\ + 0.506PKG - 0.264AREA + AF \end{aligned} \quad (2)$$

Where;

BCI = Bicycle Compatibility Index,

BL = Presence of a bike lane,

BLW = Bike lane width,

CLW = Curb lane width,

OLV = Other lane volume,

SPD = 85th percentile traffic speed,

PKG = Presence of a parking lane,

AREA = Roadside usage type,

AF = ft + fp + ftr,

AREA = Roadside use type,

AF= ft+fp+ftr,

Figure 6. Traffic Stress Level (LTS) Measurement Chart [35].

Mekuria et al. [33] developed the Level of Traffic Stress (LTS) approach, which considers acceptable stress levels of a bicycle network for different user classes based on traffic and road characteristics.

In the LTS framework:

- LTS 1 is a level tolerable by child users;
- LTS 2 is tolerable for the mainstream adult population;
- LTS 3 is tolerable for enthusiastic and confident cyclists who still prefer to have their own designated space;

Mixed traffic criteria

Number of lanes	Effective ADT*	Prevailing Speed ≤ 20 mph	25 mph	30 mph	35 mph	40 mph	45 mph	50+mph
Unlaned 2-way street (no centerline)	0-750	LTS 1	LTS 1	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3
	751-1500	LTS 1	LTS 1	LTS 2	LTS 3	LTS 3	LTS 3	LTS 4
	1501-3000	LTS 2	LTS 2	LTS 2	LTS 3	LTS 4	LTS 4	LTS 4
	3000+	LTS 2	LTS 3	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4
1 thru lane per direction (1-way, 1-lane street or 2-way street with centerline)	0-750	LTS 1	LTS 1	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3
	751-1500	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3	LTS 4
	1501-3000	LTS 2	LTS 3	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4
	3000+	LTS 3	LTS 3	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4
2 thru lanes per direction	0-8000	LTS 3	LTS 3	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4
	8001+	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4	LTS 4	LTS 4
3+ thru lanes per direction	any ADT	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4	LTS 4	LTS 4

* Effective ADT = ADT for two-way roads; Effective ADT = 1.5*ADT for one-way roads

Bike lanes and shoulders not adjacent to a parking lane

Number of lanes	Bike lane width	Prevailing Speed ≤ 25 mph	30 mph	35 mph	40 mph	45 mph	50+ mph
1 thru lane per direction, or unlaned	6+ ft	LTS 1	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3
	4 or 5 ft	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 4
2 thru lanes per direction	6+ ft	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 3
	4 or 5 ft	LTS 2	LTS 2	LTS 2	LTS 3	LTS 3	LTS 4
3+ lanes per direction	any width	LTS 3	LTS 3	LTS 3	LTS 4	LTS 4	LTS 4

Notes 1. If bike lane / shoulder is frequently blocked, use mixed traffic criteria.
2. Qualifying bike lane / shoulder should extend at least 4 ft from a curb and at least 3.5 ft from a pavement edge or discontinuous gutter pan seam
3.Bike lane width includes any marked buffer next to the bike lane.

Bike lanes alongside a parking lane

Number of lanes	Bike lane reach = Bike + Pkg lane width	Prevailing Speed ≤ 25 mph	30 mph	35 mph
1 lane per direction	15+ ft	LTS 1	LTS 2	LTS 3
	12-14 ft	LTS 2	LTS 2	LTS 3
2 lanes per direction (2-way)	15+ ft	LTS 2	LTS 3	LTS 3
2-3 lanes per direction (1-way)		LTS 2	LTS 3	LTS 3
other multilane		LTS 3	LTS 3	LTS 3

Notes 1. If bike lane is frequently blocked, use mixed traffic criteria.
2. Qualifying bike lane must have reach (bike lane width + parking lane width) ≥ 12 ft
3.Bike lane width includes any marked buffer next to the bike lane.

- LTS 4 is tolerable only for those described as strong and fearless.

Since 2007, the LTS has been revised. The LTS system is a model criterion applicable to mixed traffic and traffic situations with bike lanes, but it does not measure levels on segregated bike paths.

The latest study published in Figure 6 shows that the amounts of AADT (Annual Average Daily Traffic) passing through the roadway have also been measured for mixed traffic situations. Querg et al. [36] developed a bikeability index in Munich, Germany. Based on the city of Munich, this index measures bikeability by considering the presence and type of bike lanes, speed limits, bike parking facilities, and the quality of bicycle intersection infrastructure.

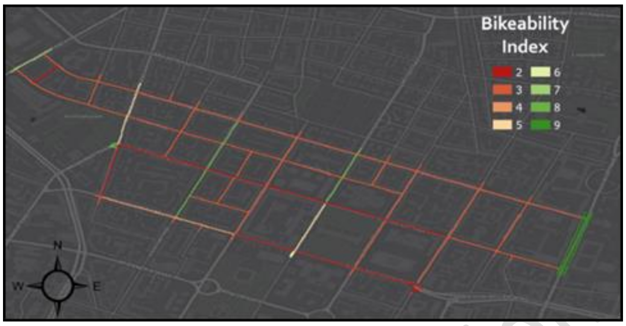


Figure 7. Weighted index data of Linear Segments and intersections [36].

Werner et al. [37] aimed to investigate cyclists' stress levels by measuring physiological indicators as an intersubjective indicator of perceived bikeability and their spatial correlation. An automatic stress perception and collection workflow was developed and validated in a case study in Salzburg, Austria.

Rodrigues et al. [38] applied an index to compare the physiological stress measurements of 15 cyclists in São Carlos, a developing city in Brazil, with the LTS. Cabral et al. [39] constructed approximately 20 km of protected bike lanes in core neighborhood streets of Edmonton, Canada, opting for a rapid and coordinated network implementation over a more traditional phased approach to bike lane construction. Hagen and Ralph [40] analyzed LTS rankings to compare parents' willingness to bike with their willingness to allow their children to bike.

Wang et al. [41] studied the relationships between bike network design and commuting mode shares in Franklin County, Ohio, USA. Bicycle traffic stress level criteria were adopted to measure the bike network. Bearn et al. [42] examined the adapted LTS system and classified bike network connectivity in two case studies to evaluate the methodology and demonstrate practical applications in infrastructure management.

Imani et al. [43] studied the level of traffic stress for cyclists on the street and trail network in Toronto, Canada. Lowry et al. [44] introduced a new method to prioritize bicycle improvement projects based on low-stress network connectivity. Bas et al. [45] proposed strategies to update trip-based transportation models to estimate non-motorized travel rates, evaluate multimodal choice models, and assess complete street plans.

Kent and Karner [46] measured how reduced traffic stress in segments of a city-wide bike network increased access to supermarkets, pharmacies, banks, and public libraries. Cabral and Kim [47] developed the Bicycle Comfort Level system using binary logistic regression and road network choices with infrastructure data from survey data in Edmonton, Canada. Caviedes and Figliozzi [48] examined real-world physiological stress measurements of cyclists traveling between bike facilities during peak and off-peak traffic times.

4.1.3 Intersection Studies

One of the areas of bicycle infrastructure studies is the examination of intersections. Intersections are one of the most challenging structural elements for cyclists to navigate. Various studies have been conducted on intersections, but advanced research is still lacking. Twelve articles on this topic were reviewed in the literature, focusing on bicycle infrastructure at intersections, riding by intersection type, user behavior at intersections, intersection safety, and sight distance at intersections.

From the reviewed articles, Deliali et al. [49] found that protected bike lanes motivate less attention to cyclists traveling in these lanes, thus reducing drivers' ability to perceive cyclists. Additionally, they found that protected intersections lead to a higher rate of looking right before making a right turn at the intersection. Drivers who glanced at the intersection were found to travel at lower speeds, indicating a correlation between the presence of protected intersection elements and speed selection.

Singleton and Paudel [50] surveyed 568 adult cyclists in the U.S. to understand the perception of roundabouts from the cyclists' perspective when transitioning from traditional intersections to roundabouts. While most current cyclists (71%) reported feeling somewhat comfortable riding in roundabouts, about one-third (29%) expressed discomfort.

Scoot et al. [51] conducted a bicycle simulator study to understand better the impacts of three different intersection treatments (i.e., bike boxes, mixing zones, and bicycle signals) on cyclists' comfort, stress levels, and riding behavior. This allowed the researchers to recommendthe most effective design to reduce vehicle-bicycle collision risks at signalized intersections.

Using a case-control study, Zangenehpour et al. [52] investigated the safety impacts of bike lanes at signalized intersections. More than 90 hours of video from 23 intersections were collected and processed to obtain the trajectories of cyclists and motor vehicles. The data indicated that intersections with bike lanes on the right were safer than those without bike lanes.Gitelman et al. [53] conducted observational studies to characterize the typical behaviors of adult e-cyclists in various urban environments in Israeli cities. Traffic counts, speed measurements, and video recordings were documented in the study.

Bai and Sze [54] aimed to identify the irregularities of cyclists running red lights, considering the effects of bike type and group size. The results showed that e-cyclists were significantly more likely to run red lights than traditional cyclists.Singleton and Paudel [55] reviewed numerous studies from 49 sources, observing interactions between accident data and driver/cyclist behavior. The study found that the bicycle safety situation was worse for multi-lane roundabouts when bike lanes were provided on the roadway.

Mohammadi et al. [56] modeled vehicle-bicycle interactions at unsignalized intersections, indicating that cyclists rely solely on kinematics (speed and position) without behavioral cues such as pedaling or hand gestures.Kircher and Ahlström [57] investigated how drivers and cyclists pay attention to urban intersections, using the minimum required attention theory and the attention, effort, expectation, value model. They explored how challenging it is to meet these requirements.

Ng et al. [58] examined which types of bicycle infrastructure cyclists perceive as the safest at unsignalized intersections. General linear mixed modeling was used to examine the relationships between safety perceptions and 12 types of bicycle infrastructure in three different driver-cyclist interaction scenarios. Off-road bike paths and trails were perceived as the safest bicycle infrastructure at unsignalized intersections.Gomez and Castro [59] assessed the visibility of an urban intersection in Madrid, Spain, from a cyclist's perspective. The study focused on intersection sight distance (ISD), the distance a driver has to effectively and safely perceive and react to conflicting trajectories without having the right of way.Madsen and Lahrmann [60] compared the safety of cyclists at signalized intersections with different traffic volumes in five bike facility scenarios to evaluate which setups were better for cyclist safety.

Figure 8. Different intersection bicycle facilities used in the study[60].

4.1.4 Passing (Lateral) Distance

One of the concerns cyclists face, particularly in bike lanes and mixed traffic, is the passing distance from vehicles. In this study, ten articles related to passing distance were reviewed. These articles examined bicycle infrastructure at intersections, passing distance studies using experimental bicycles, lateral distance-user behavior, and safety in lateral distance situations.

Rubie et al. [61] identified 42 articles reporting 36 independent studies on lateral passing distance (LPD) in the studies on cyclists' lateral distance. Significant positive relationships were found between LPD and road width and speed limit. Seven out of eight studies found that the closer the cyclist was to the curb, the larger the LPD. Apasnore [62] examined cyclist comfort in mixed traffic in Ottawa, Canada. Cyclists rode slightly further from the curb on two-lane roads than single-lane roads; 90% of the passes were over 1.23 meters. The lateral gap between bicycles and vehicles was positively correlated with motor vehicle speed, lane width, and the cyclist's position relative to the adjacent curb line but negatively correlated with traffic density and bicycle speed.

Beck et al. [63] conducted an observational study on the road in Victoria, Australia. Participants' bicycles were equipped with a special device, and rode as usual for one to two weeks. A hierarchical linear model was used to investigate the relationship between motor vehicle and infrastructure characteristics (location, presence of a marked bike lane on the road, and the presence of parked cars at the curb) and passing distance (defined as the lateral distance between the end of the road and the road). In their study, Mackenzie et al. [64] examined how passing distances and compliance with minimum passing distance were affected by various parameters in a natural cycling study. The study found that differences in passing distances and non-compliance with minimum passing distance were associated with road classification, presence of bike lanes, and speed limit..

Figure 9. Dual ultrasonic distance meters mounted on bicycles for the study [64].

Feng et al. [65] examined driver-cyclist interactions from the driver's perspective using in-vehicle sensory data obtained from natural driving. The lateral positioning of the vehicle as the cyclist passed was also investigated as an additional factor in the study. Walker [66] used an equipped bicycle to collect proximity data from overtaking drivers in a natural experiment. Contrary to common belief, the relationship between the driver's position and overtaking proximity was found. Beck et al. [67] conducted another observational study on the road in Victoria, Australia. Participants' bicycles wereequipped with a handlebar-mounted "panic button" to measure the lateral passing distance of motor vehicles. They could be pressed when participants felt a passing event was too close or unsafe. The relationship between the cyclist's gender, type of motor vehicle, and infrastructure characteristics with panic button events was investigated.

Rubie et al. [68] examined natural passing events on urban roads in Queensland, Australia, through an online cross-sectional survey. Narrow passing distances, parked cars, oncoming traffic, and high vehicle speeds indicate unsafe passing situations for cyclists. Fernandez et al. [69] measured the situations of car-bicycle collisions and the distance between the two transportation modes when a passenger car and a bicycle move in the same direction on the same road. Stülpnagel and Binning [70] surveyed gap distance, asking people about physical cross-sections in areas with parking. The study found that if there was a 3.5-meter or wider bike lane in areas with parking, a 25 cm edge line was needed on the right, and if the bike lane was 2 meters, a 75 cm linear gap was needed between the parking and the bike lane.

4.2 Factors Related to Bicycle Users

4.2.1 User Behavior

Cyclist behavior is defined as the interaction of cyclists with the surrounding infrastructure, vehicles, and natural conditions while riding. Understanding user behavior conditions helps bicycle facility designers establish bicycle facilities. Eight articles related to behavior were reviewed in the literature, examining hazard perception, riding safety, bicycle use behavior, the impact of bicycle infrastructure on users, and user stress.In the studies, Guo et al. [71] used a bicycle simulator within a virtual environment to efficiently and safely understand cyclists' behavioral and physiological responses. The study utilized ready-to-use sensors to measure cyclists' performance (speed and lane position) and physiological responses (eye tracking and heart rate). The results showed that protected and regular bike lanes provided very safe outcomes for many examined parameters compared to cycling in mixed traffic.Kovacsova et al. [72] conducted a video survey to examine hazard perception for cyclists. This conceptual study aimed to develop PC-based hazard perception training for experienced cyclists and to evaluate its short-term effectiveness using hazard perception tests.

Figure 10. Video survey Mode 1 study images implemented in the Netherlands [71].

Boisjoly et al. [73] evaluated the performance of the bicycle network in Montreal, Canada, using a set of complementary indicators that account for the directness between the observed origin and destination points of cyclists. Goel et al. [74] used a combination of urban, regional, and national travel surveys from 17 countries across six continents from 2009 to 2019. The study presented a descriptive analysis of bicycle use behavior, including levels of cycling, trip purposes, distances, and user demographics for 35 major cities and 11 countries.

Janssen et al. [75] examined the effects of different types of pavement stones on cyclist and pedestrian behaviors. The study found that cyclists riding on the sidewalk created normal situations for all types of sidewalks, with no observed conflicts between cyclists and pedestrians.Fournier et al. [76] used a driving simulator to investigate driver behavior in interactions with cyclists when cyclist interactions do not trigger driver behavior. This research aimed to investigate the conditions of driver behavior in each treatment type based on cycling frequency, familiarity with improvements, and their combined effect.

Fitch et al. [77] conducted an experimental study on cyclist stress using heart rate variability. The relationship between heart rate and road environment was examined using a multi-level statistical model, showing that participants' heart rates differed significantly in only one of the five tested road environments (local road).Gitelman et al. [78] aimed to characterize the scope of Alternative Transportation Modes (ATM) usage, typical behaviors in urban environments, risk factors, and solutions for safer integrating ATMs into urban areas in Israeli cities.

4.2.2 Experimental (Instrumented) Bicycle Studies

Experimental bicycle studies in recent years have been conducted in various countries to obtain more concrete data from bicycle users and develop accurate approaches based on this data. The literature review examined nine articles related to instrumented bicycle studies. These articles covered bicycle infrastructure maintenance, user stress, user behavior and safety, cyclist safety, weather conditions and safety, and bicycle comfort.

In this section, Marchiori [79] sought solutions to the maintenance problems of bicycle paths. A system was developed to collect data from bicycle paths economically, and experiments were conducted to see if the data allowed for reliable condition prediction. Gadsby et al. [80] investigated the attitudes and effects of stressors on cyclists using survey techniques and semi-naturalistic cycling in Delft, Netherlands, and Atlanta, Georgia. The study found that the most effective stressors were motor vehicles, sidewalks, and poor infrastructure.Liu and Suzuki [81] conducted a study in four different Japanese cities using instrumented bicycles to measure the impact of e-bikes in urban and rural areas. The study concluded that e-bikes suit short-distance trips in cities and consume less energy than conventional bicycles, especially on hilly roads.

Werneke et al. [82] contributed to the research by collecting information on cyclists' behavior and safety not typically found in traditional data sources through a naturalistic cycling study.Dozza et al. [83] presented a framework for the data-based evaluation of micromobility vehicles. The study utilized experience from evaluating bicycle dynamics in real traffic to make objective and subjective comparisons between different micro-mobility solutions, showing that e-scooters, despite requiring longer braking distances, have more maneuverability than bicycles.

Lee et al. [84] used the existing literature in cognitive science on driver behavior to model the experimental results from field trials of bicycles. They modeled braking and steering maneuvers from field data on cyclists avoiding obstacles in their comfort zones.Fenre and Paste [85] examined the effects of typical winter conditions on bicycle rolling resistance and comfort to facilitate increased winter cycling. An instrumented bicycle was used to measure rolling resistance under various winter conditions on streets and bike paths in Trondheim, Norway.

Gao et al. [86] conducted field tests on a total of 46 sections of 24 urban roads in Xi'an, China. An innovative Dynamic Bicycle Comfort (DCC) measurement system consisting of an accelerometer, GPS recorder, and smartphone was used to record dynamic data such as vibration, track, speed, and mileage. The study found that comfort level was directly proportional to acceptable vibration levels and inversely proportional to perceptible vibration levels.Zhu and Zhu [87] developed a Bicycle Comfort Index using an instrumented bicycle to automatically measure the comfort level of the traveled route by capturing automatic infrastructure objects and considering infrastructure parameters..

4.3 Environmental Factors

4.3.1 Noise and Air Pollution

Noise and air pollution are among the most important issues for creating sustainable and clean cities in the future. Nine articles were reviewed on this topic, examining the relationship between air pollution and traffic, the relationship between air pollution and noise, user interaction with noise, and the relationship between infrastructure and noise.

Bosen et al. [88] analyzed the relationship between air pollution, traffic, and the risk perceptions of cyclists, as well as how these risks are mitigated. Insights were gained into the habits of professional cyclists and the factors influencing a bicycle-friendly mobility culture. Apparicio et al. [89] assessed cyclists' exposure to air pollution and noise in neighborhoods in downtown Montreal and sought to determine the effect of relevant local factors such as weather, day, time, road type, and bike path on exposure. Average exposure was 70.5 dB(A) for noise and 76 μg/m^3 for nitrogen dioxide (NO2).

Soni et al. [90] examined the environmental impact of vehicle traffic noise in Mumbai, India, with average peak values reaching 85 dB(A) due to vehicle movements. Ising and Kruppa [91] found evidence of increases in chronic stress hormone disorders and ischemic heart diseases corresponding to established endogenous risk factors under the noise stress hypothesis. According to the Environment Council, daytime noise levels exceeding 65 dB(A) showed a trend towards increased cardiovascular risk.

Can et al. [92] formed an interdisciplinary team of seven researchers focusing on various aspects of acoustics and mobility, examining the potential impact of ongoing mobility and societal changes on sound. Gelb and Appricio [93] measured NO2 and dB(A) levels with over 560 hours of video recording and approximately 9,350 km of cycling in Paris, Lyon, Copenhagen, Delhi, Mumbai, Montreal, and Toronto. The highest NO2 concentrations were found in Delhi (average = 200 μg/m^3) and Lyon (190 μg/m^3). Delhi and Mumbai were the cities with the highest noise exposure, with averages of 79.3 and 79.4 dB(A) LAeq 1 minute, respectively.

Lu et al. [94] developed structural equation models to investigate the mediating effects of road characteristics on traffic noise through traffic flow using data from field measurements in Dalian, China. The results showed that the number of lanes affected traffic noise regarding vehicle numbers. Zhao et al. [95] developed various noise monitoring and simulation techniques to measure and evaluate urban sounds. Begou et al. [96] measured road traffic noise levels in Thessaloniki, Greece. An important result of the study was that systematically combining various dimensions of a bicycle network's quality, such as flatness, connectivity, safety, and reduced exposure to air and noise pollution, can be challenging.

Figure 11. Noise level analyzer (Solo Master) and microphone used in measurements[95].

4.3.2 Weather Conditions

One of the most adverse conditions for cycling is weather. In countries where cold and rainy weather is prevalent throughout the year, cycling is negatively affected by adverse weather conditions. Although there are not many articles in the literature on weather conditions, only two articles were reviewed. These articles addressed the relationship between winter conditions and infrastructure and winter conditions and cycling.

Cai and Pei [97], considering the Chinese practices in winter maintenance of bike paths, analyzed the characteristics of bicycle travel in cold-climate cities. They noted that the bike-sharing rate in China's cold-climate cities significantly decreases in winter, and the larger the temperature difference, the greater the decline. Bergström and Magnusson [96] examined attitudes toward winter cycling in general..

5 Conclusions and Suggestions

Developed countries worldwide, especially during the pandemic, have been intensely working to increase the usage of conventional and electric bicycles, which are considered vulnerable users. The adverse economic conditions, rising injuries and fatalities in traffic, increasing healthcare expenses, deteriorating air quality, rising noise levels, and the increasing amount of time spent in traffic all highlight to authorities why people should be encouraged to use bicycles.

Countries like Denmark, Sweden, the Netherlands, Germany, Norway, Japan, Finland, and China have managed to increase the daily use of bicycles to 10% and above [11]. In countries such as France, Spain, the United Kingdom, the United States, Canada, and Australia, bicycle usage levels rise steadily through incentive programs.

The study included a literature review on traffic infrastructure, environmental factors, and user behavior. A total of 95 articles were translated from foreign sources. Under infrastructure, factors include traffic and user stress studies, traffic infrastructure and safety, bicycle use at intersections, and bicycle passing distances. Under environmental impact, noise, air pollution, and weather conditions were reviewed. Under the bicycle user category, experimental bicycle studies and cyclist behaviors were investigated.

Within the scope of the study, all literature studies examined worldwide and in Turkey have shown that experimental studies are mandatory to increase bicycle use and make it safer and that the studies should be carried out in the field with equipment.

Recent studies on bicycles worldwide show that there is an increase in publications on experimental bicycle studies, traffic infrastructure-related stress, user stress studies, crossing distance studies, cyclist behavior, and intersections and that there is not enough research on noise, air pollution, and weather conditions. It has been understood that for cyclists to ride bicycles safely in cities and increase bicycle usage rates, hardware and simulation studies on traffic infrastructure and environmental factors should be accelerated.

However, as seen in developed countries, the constructed paths do not generate demand for use. The primary reasons for this include safety deficiencies and lack of comfort. Therefore, the results in the literature studies show that the field studies to be conducted are important. Bicycle paths currently constructed or planned to be constructed show that every road route should be examined, and corridors and intersections should be supported with different studies regarding infrastructure, environment, and user behavior. It shows that the countries that conduct field studies and discuss their results have increased their cycling status.

Additionally, the following steps should be taken to increase bicycle use in urban transportation in Turkey:

1) Address traffic safety and infrastructure specifically concerning bicycle rideability.
2) Evaluate the existing road network for bicycle rideability.
3) Develop a bicycle rideability method incorporating traffic stress levels and other factors for existing and proposed bicycle paths and corridors.
4) Design mobile measurement bicycles capable of collecting data from the existing road network.

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7 Author contribution statement

Author 1 contributed to the literature review and gathering of the literature and interpretation of the results, Author 2 contributed to the evaluation of the results, and Author 3 contributed to the control and correction of English sentences.

8 Ethics committee approval and conflict of interest statement

“There is no need to collect the prepared medical ethics committee permission.” “The article prepared has no conflict of interest with any person/institution.”

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