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A Survey of Technologies and Recent Developments for Sustainable Smart Cycling

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Abstract: Among the problems resulted from the continuous urbanization process, inefficient urban mobility and high pollution levels have been complex challenges that have demanded a lot of public investments and research efforts. Recently, some alternative transportation means have been leveraged as sustainable options for such challenges, which has brought bicycles to a more relevant setting. Besides the sometimes obvious benefits of adopting bikes for transportation, technologies around the Internet of Things (IoT) paradigm have been advocated as important supportive tools to boost smart cycling initiatives. Actually, new technologies can be exploited to improve the efficiency of bike paths and parking spots, while reducing accidents and enhancing the cycling experience of the users. Therefore, in this highly vibrating scenario, this article facilitates the understating of current research trends and promising developments, surveying and classing recent works. Since there is a global interest for the promotion of cleaner and more sustainable solutions in large cities, this survey can be valuable when supporting new developments in this highly relevant research area.

Keywords: smart cycling; sustainable mobility; smart cities; Internet of Things; bike sharing

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1. Introduction

Nowadays, most people live in large or mega cities around the world, which has resulted in a way of living dominated by urban patterns [1]. However, while the benefits of the fast urbanization process in the last hundred of years have been largely praised, a series of problems have also emerged in our increasingly overcrowded cities [2,3]. As a result, modern urban areas have been struggling to deal with complex challenges such as mobility, pollution and sustainable use of resources, with promising initiatives emerging in the last years [4,5].

A major challenge that is recurrent in most large cities is the urban mobility [6]. The impact of inefficient transportation has been extensively discussed, since the hours spent due to heavy traffic can be easily associated to economy losses [7]. Additionally, other issues related to public health like traffic deaths and serious injuries can also be collateral effects from mobility inefficiencies of large cities. However, although these problems could be already enough to trigger the red alarm for better planning and management of the cities, traditional vehicles are also major sources of pollution, directly impacting the air quality in urban areas. The resulting scenario has put mobility issues on the top of the list of urgent problems to be solved, but experience has demonstrated that efficient solutions for such issues are not straightforward [8,9].

One of the most promising trends to relieve traffic jams and all their associated negative impacts is the use of alternative transportation means. Among them, bicycles have been the most successful option, with reasonable efficiency at very affordable costs. In recent decades, some governments have been investing in the construction of bike paths and in the reduction of taxes for the fabrication of bikes, potentially stimulating the use of bicycles at least for short-distance routes [10,11]. In parallel, a new generation of electric bicycles and scooters is getting very popular, but their usage and mobility challenges are quite similar to the ones experienced by conventional bicycles. Actually, when promoting more sustainable mobility, bicycles, electric bicycles, electric scooters, skates and rollerblades are all alternative transportation means that will usually share the same challenges and interests, leading us to collectively call them "bikes" for simplification reasons.

In this scenario, the concept of "smart cycling" has emerged as a new step to improve the experience of the cyclists, their safety while moving and the perception of bikes as an active element of the urban technological ecosystem. For that, the use of new hardware and software technologies, as well as the construction of public policies, have been leveraged to support initiatives toward more efficient use of bikes. Hence, there is a direct connection between the improvement of bikes as effective transportation alternatives and the rise of smart cities, since they are both based on similar principles and paradigms.

Table 1 presents the current panorama of road accidents and smart cycling efforts over the world, depicting different economical realities [12–15].

Table 1. Global panorama for roads accidents and smart cycling efforts in different countries.

Parameters	Low Income	Middle Income	High Income
Population in thousands (2020)	775,711	5,753,052	1,263,093
Gross Domestic Product (GDP) in US$ (2019)	$541.512 billion	$32.153 trillion	$55.141 trillion
Estimated road traffic death rate per 100,000 people (2019)	28.34	17.1	8.39
Human impact of road injuries: new costs every year	$27.4 billion	$1210.7 billion	$973.8 billion
Percent of countries with cities committed to an increase in modal share of cycling	0%	7.1%	30.1%
Number of cities committed to increase cycling modal share	0%	4 (3.78%)	65 (33.5%)

Actually, investments in cycling are uneven across the world, as depicted in Figure 1. According to the European Cyclist's Federation [12], about 70 cities around different continents have committed to an increasing in the modal participation of cycling, most of them placed in high-income countries.

A crucial element to change this reality is the supporting of smart cycling initiatives. Recently, with the popularization of new personal gadgets and smartphones, important solutions have emerged in that direction [16]. Apps based on crowd-sourcing techniques have become common services, indicating faster and safer alternative roads. Bike-sharing applications are becoming popular, strongly facilitating the use of bikes as a last-mile option [17]. In parallel, Internet of Things (IoT) technologies are being used to endow bikes with unprecedented services. With more solutions emerging almost in a daily basis, smart cycling is gaining an important momentum.

This article surveys recent developments concerning the use of new technologies to support the use of bikes as an effective transportation mean in urban areas. With the increasing interest in the construction of more sustainable cities [5,18], efficient mobility has been sought through different solutions, benefiting different areas including smart cycling. Therefore, this article will organize and classify promising solutions, discussing challenges and technologies that can enhance the way bikes can be inserted into the dynamics of the urban scenarios. Moreover, research directions will be envisioned, guiding new research efforts in this area.



Figure 1. The right to cycle: cities that have committed to a targeted increase in modal share of cycling. Source: European Cyclist Federation.

The remainder of this article is organized as follows. Section 2 summarizes previous survey works in the areas of urban mobility, bike-centric transportation and smart cycling. The use of new smartphone-based applications is surveyed in Section 3, highlighting global initiates and promising solutions to enhance the use of bikes. The new possibilities for smart cycling that are emerging due to the IoT revolution are discussed in Section 4. Section 5 presents advantages and challenges for the adoption of e-bikes, advocating for their interconnection as an important foundation for future smart cycling. Some important research directions are envisioned and discussed in Section 6. Finally, conclusions and references are presented.

2. On the Use of Bikes in Cities

Generally speaking, sustainable mobility innovations are at the forefront of large urban centers. With increasing challenges resulted from inefficient mobility, air pollution and traffic accidents constantly gaining attention in large cities, new solutions have been sought in different areas and contexts. In fact, for an increasing number of cities, the solution for such challenges has been expected from the adoption of bikes.

Many works have considered the adoption of bikes as an effective way to enhance mobility in urban areas, addressing different aspects of urban cycling. Since there are different particularities according to the way bikes are used on the considered regions, the literature has provided many important insights about the development of smart cycling in different countries. Table 2 summarizes recent works in this sense, indicating important discussions that have driven research efforts.

Actually, there are many challenges related to smart cycling, ranging from political and economical issues to the use of new disruptive technologies. Although all these discussions are relevant, we are particularly concerned with technological innovations that will pave the way for the construction of smart cycling. Among them, we believe that the massive use of smartphones and the adoption of IoT devices will be the core elements to foster bike-centric mobility, with potential benefits that can dramatically change the cities' transportation services [19]. Therefore, this article surveys recent works targeted at innovations that can ultimately support the maturation of smart cycling in cities, contributing with important discussions in this area.

In short, the discussions in this article are centered on three major research trends: smartphone-based cycling, IoT-bikes and connected e-bikes. Figure 2 further depicts the research areas and development initiatives that are surveyed in this work.

Table 2. Research works discussing cycling initiatives and recent developments to promote the adoption of bikes.

Work	Year	Country	Subject	Presented Discussions
MacArthur et al. [20]	2014	USA	E-bike	This work surveyed the purchase, cycling decisions and preferences concerning the use of e-bikes
Popa et al. [21]	2017	Italy	Safety and health	The use of helmets among cyclists is investigated. Authors observed that male cyclists are more likely to wear helmets, as well as those who ride long distances or had accidents before
Vith and Mössner [10]	2017	USA	Bike paths	It associates different requirements concerning city officials, cycling associations and transportation planners when creating bike paths. Social and economical concerns are raised
Caulfield et al. [22]	2017	Ireland	Bike sharing	The challenges and benefits of bike sharing in a small city are discussed, raising comparisons to larger cities
Zhang and Mi [23]	2018	China	Bike sharing	This work investigates the benefits of bike sharing systems for the environment, accounting the emission of carbon dioxide and nitrogen oxide
Pokorny et al. [24]	2018	Norway	Accidents	Road accidents involving bikes and trucks are investigated, with important discussions about the accidents areas
Bernardi et al. [25]	2018	The Netherlands	Bike paths	The use of smartphones by cyclists is analyzed, indicating the use of apps and preferences to assist routes planning
Majumdar and Mitra [26]	2018	India	Bike paths	This work discusses the importance of adequate infrastructure as a way of encouraging the use of bikes for transportation
Zheng et al. [27]	2019	China	Bike sharing	This work investigates how bike-sharing solutions reduce the environmental impacts caused by transportation, analyzing different cycling behaviors
Luísa da Costa Lage and Rodrigues [28]	2020	Brazil	Bike delivery	The impacts of the COVID-19 Pandemic on delivery workers using bikes and motorcycles are discussed, considering different factors
Hua et al. [29]	2020	China	Parking	The challenges of bikes parking without docking stations are discussed in this paper. Authors investigate the use of clustering algorithms as a way to tackle this problem
Sun et al. [30]	2020	The Netherlands	E-bike	This work aims to identify the groups of people who are more likely to replace their cars for e-bikes based on socio-demographic analysis
Ortiz-Prado et al. [31]	2020	Ecuador	Safety and health	The rate of infection by SARS-CoV-2 in cyclists and motorcyclists is investigated, when delivery services are being provided
Castañon and Ribeiro [32]	2021	Portugal	Infrastructure	This work does a literature review towards the concept of Bikeability, discussing issues such as safety, comfort and efficiency of cycling infrastructure
Plasencia-Lozano [33]	2021	Spain	Bike paths	The impacts of bike paths implantation is reviewed. Two surveys were applied in different moments as an attempt to evaluate such impacts in a city

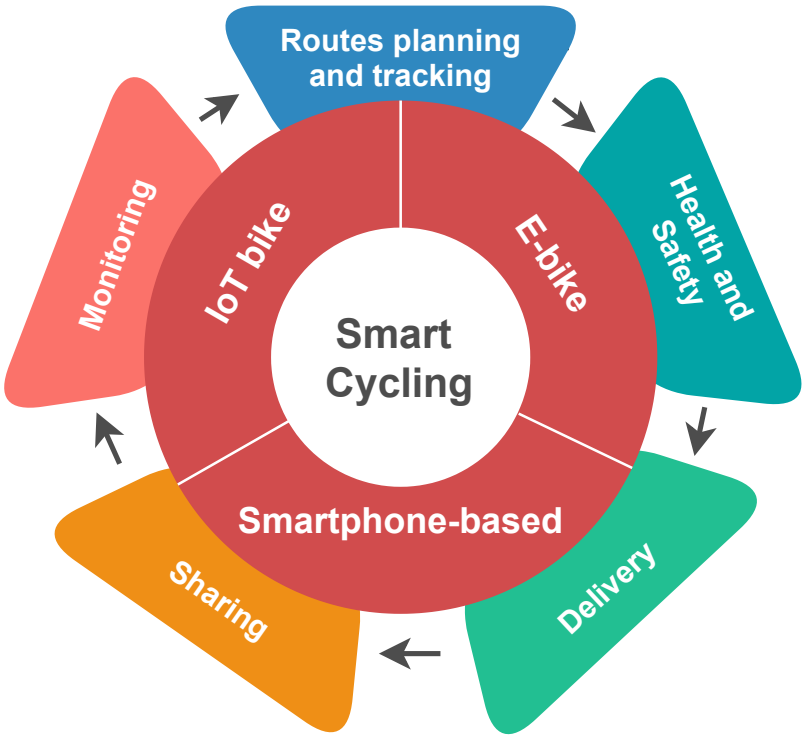


Figure 2. The surveyed research areas and applications.

Next sections will discuss new technologies and innovative projects targeted at the promotion of more efficient, affordable and safer cycling in cities, highlighting their expected impacts when achieving sustainable urban mobility.

3. Bikes in the Age of Apps

The use of smartphones has become essential in modern life. Among other reasons, this is due to the ease of communication that this type of device provides, in addition to the availability of an immensity of smartphone-based applications with different purposes [34]. With the development of more powerful devices at affordable prices, the number of active smartphones has even surpassed the number of traditional computers, signaling an important transformation on the way information has been consumed. Supported by this propitious scenario, it is estimated that over three billion people were using smartphones by the end of 2020, but it is still an actively growing number [35].

This large number of users has been boosted by popular virtual markets for mobile applications, which provide millions of apps for different purposes [34]. For this huge amount of applications, or simply "apps", a particular group has been dedicated to facilitate the use of services related to daily activities, supporting users according to their needs, habits or interests [35]. When coming to the use of bikes in modern cities, such apps have been an important breakthrough for the adoption of sustainable transportation.

Among smartphone apps that seek to facilitate the people's lives, there are applications that can affect the daily mobility in certain spaces. In this context, one of the main purposes of some apps is to solve problems related to urban mobility. Actually, such applications have allowed smartphones to use mobile data (mostly supported by 4G/5G technologies and Wi-Fi networks) and location-based services (GPS) in order to provide real-time information about public transportation systems. In short, such apps have supported route planning according to the user's current position, as well as allowing the identification of more efficient public services and even the indication of nearby rental spots for shared bicycles [16]. In fact, these have been very important transformations in the way people interact with the urban environment.

Actually, the rise in the use of smartphones has also allowed connections with several socio-technical innovations that have been seeking to enhance urban mobility systems towards sustainability [36]. This development trend is motivated by the possibility of increasing the efficiency of existing transport systems and the use of sustainable transportation alternatives. Among common goals when employing such apps, there is an inherent desire to minimize the use of traditional vehicles, potentially reducing the emission of pollutants, relieving heavy traffic configurations and preventing traffic accidents [36]. One of the most efficient ways to achieve these goals is fostering the adoption of bicycles and other transportation alternatives, leveraging the use of smartphones and supportive apps as important tools in this process [16].

Figure 3 presents a general schema depicting a typical urban cyclist, highlighting the availability of some popular smartphone-based services to support the use of bikes for mobility.

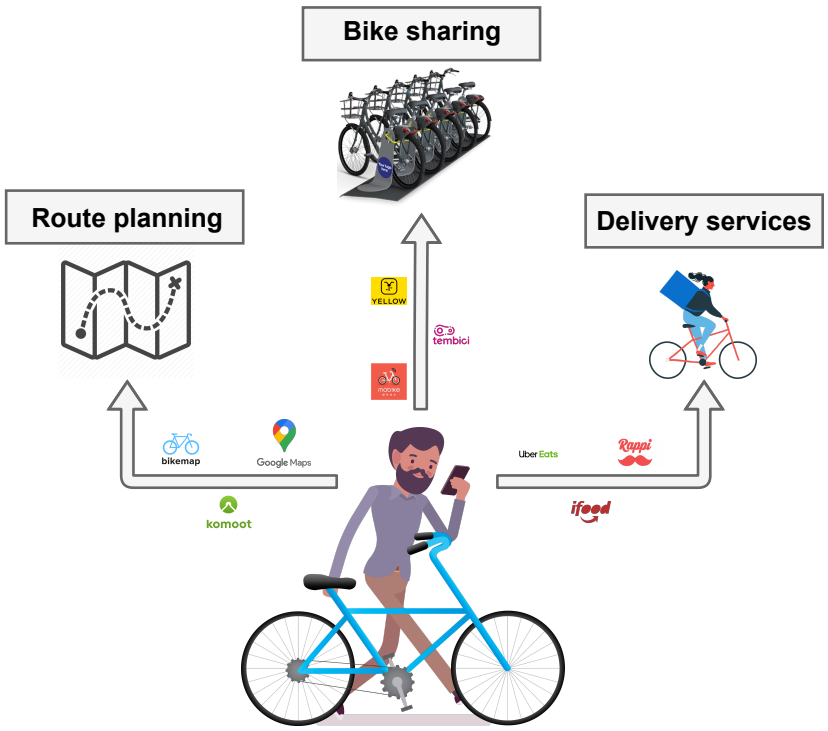


Figure 3. Smartphone-based services to support the use of bikes.

In recent decades, different initiatives have emerged to support the use of bikes for transportation in urban areas [37]. In addition to encouraging the use of bikes as an effective option for urban mobility, comprising the construction of bike paths and funding public policies toward cycling, other factors have contributed to an increasing in the number of cyclists in large cities. In this scenario, the use of new smartphone-based technologies has played an important role. Actually, regardless of the purpose when using bicycles, there are several mobile applications that can assist cyclists by inserting them into the smart cycling environment. These apps aim to make the cycling experience more efficient, healthy, comfortable, safe and satisfying, providing some important results.

Next subsections present and discuss the three most common services provided by smartphone apps in this scenario.

3.1. Route Planning

Despite the use of bikes for daily transportation has been much discussed in recent years, most cities around the world do not have adequate infrastructure for efficient cycling [38]. Given the aforementioned circumstances, it is very important to provide

valuable information for cyclists concerning available paths, potentially alleviating the already known mobility problems [39].

The issue of routing planning is not new, with many research works proposing efficient solutions to improve mobility efficiency [40,41]. In general, the main research effort has been to find the fastest route from the origin to the destination, taking into account the costs of each available path. Among such costs, distance, traffic, accidents rate and tolls are some common parameters that have been processed as cost weights. And this same principle can be leveraged when processing bike paths.

One of the most important information provided by smartphones is the current GPS (Global Positioning System) coordinates of the device. This information has been exploited by different applications, which have used spatial data to provide some important expected services for bike users. Actually, GPS coordinates can also be exploited along with data provided by embedded sensors, enlarging the perception of the users within the modeled system. In practical means, smartphones are able to send and receive spatial information about bike paths to take, guiding cyclists in urban areas [42].

Overall, route planning applications have as their main function the provision of pre-trip information for cyclists, which are usually combined with navigation data during travel in order to make changes to the routes if necessary. Basically, these apps work following two different principles: route choice and route optimization [43].

The first operation in route planning is an inherent complex task since it involves a set of route options that will be chosen based on the cyclist's preference (purpose of the trip, cyclist's physical characteristics, traffic, etc.). In [44] a survey was carried out involving 35 different routes to analyze the main selection criteria used by cyclists. It concluded that most participants were looking for characteristics such as "fast", "safe", "simple" and "attractive" for the routes they would take. Similar conclusions might be inferred from [45]. Thus, it is reasonable to say that there are some guiding rules that have been considered when implementing such solutions, ultimately supporting the adoption of bikes for transportation.

After completing the route selection process, the chosen route is usually optimized in a digital environment, being properly displayed to the user [46]. For this group of applications, in fact, many apps have been created, some of them becoming popular options. Actually, route planning may be the target service to be provided, but it may also be only a supportive resource that will enable the execution of other services for the users. Table 3 summarizes some of these apps, highlighting their main characteristics.

Table 3. Popular smartphone apps that exploit some level of route planning.

App	Main Service	Release	Bike-Centric	Free
Bikemap	Route planning	2014	x	x
Busby	Road safety	2019	x	x
Glovo	Food delivery	2015		x
Google maps	Route planning	2005		x
GSMtasks	Route planning	2019		
iFood	Food delivery	2011		x
Komoot	Route planning	2010	x	x
Rappi	Food delivery	2018		x
Routific	Route planning	2012		
Uber eats	Food delivery	2014		x

Among the presented apps in Table 3, there are options that exploit route planning as their main purpose, sometimes targeting at the use of bikes as a primary objective. However, there are those that use route planning in a secondary way, just exploiting it as a background service. Whatever the case, since the development of routing algorithms has significantly evolved in the last years, the global objective of smart cycling has been improved by such apps.

Some research works focused on bike-centric route planning have been proposed in the literature. In [47], authors created a mobile app based on Fuzzy logic that is able to perform route planning between two bike-sharing stations. For that, the route selection criteria is based on four elements: time, distance, pollution and safety of the path. Considering more information when taking decisions, that work could potentially improve the experience of the cyclists when they are moving on a city. Still considering this optimization scope, the work in [48] addresses the development of a routing application capable of helping cyclists to choose the most optimized route, taking not only the origin and the destination points, but also the sequence of stations they must visit for borrowing/exchanging/returning the bikes. The contributions in both works indicate that route planning for bikes should compute other elements than the usually considered data by traditional apps.

Finally, a study in the Netherlands processed approximately 3500 routes traveled by 280 cyclists, using the GPS of the participants' smartphones as reference [25]. That data was used to analyze route planning regarding the use of smartphones when assisting routes choosing. These analyses concluded that the considered population was very accustomed to the practice of cycling linked to the use of smartphones to support route planning, indicating that this is a largely adopted practice, although additional studies in other countries are still required [25].

3.2. Delivery Services

With the unforeseen events of the COVID-19 Pandemic beginning in 2020, important transformations took place in the society. In a very short period of time, social distancing measures were required, impacting different elements of the routine of billions of people. In this new social setting, the use of delivery services, especially for food, has become essential in the lives of many citizens around the world. Smartphone apps aimed at this purpose became even more popular, and new solutions were created. Actually, when bikes were employed to reinforce smartphone-based delivery services, such apps started to be used more often by cyclists [49]. However, the cities are still not adapted to higher demands of delivery services, especially when bikes are being used as a working tool.

Given this particular scenario, there was a significant increase in the demand for companies working in the domestic delivery sector. As an example, the app "Rappi" declared a growth of 30% in deliveries in the Latin America region due to the COVID-19 Pandemic [50]. In parallel to such growth, there was also an increase in the number of registered worker deliverers, who mostly use their own bikes to work. When we associate the inherent risks of cycling in most cities with the delivery demands of this service, it is easy to see how problematic this working configuration can be. Therefore, finding new solutions for this complex scenario should be a major concern of the governments when defining public policies.

Among the many challenges faced by domestic delivery services, the apps companies have focused on solutions to increase profit, instead of improving the safety of cyclist workers for delivery apps. One of such adopted solutions has been to support renting initiatives that would potentially increase the number of available workers. However, the impacts of more cyclists rushing against the clock on roads primarily made for motor vehicles have been completely neglected [11]. Nevertheless, if bikes are expected to be used as a profitable and safe alternative for both companies and workers (who are not even saw as employees in most cases), the current delivery model still needs to be significantly improved [28].

Some research works have analyzed important issues related to the food delivery service performed by cyclists. In [51] there is a mapping of technological innovations that might help to evolve smart cycling initiatives. Among these innovations, the authors address customization service experiences, providing a variety of supposedly desirable changes in how cycling can be experienced and what it can mean in people's lives in general. An example of this type of innovation is the food delivery service, allowing people to order something they want to eat from a certain restaurant without worrying about

going to the establishment. Since this may become a basic service for decades to come, urban planning should consider alternatives to support delivery services, including even the construction of special infrastructure.

In [28], a social analysis is carried out on the profile of cyclists delivering food in the face of the COVID-19 Pandemic scenario. In that work, the authors make an overview of the social conditions, race and gender that are "standard" characteristics when analyzing the groups of these workers. In addition, that work discusses aspects such as motivation to start making deliveries, with unemployment as the factor with the greatest impact. Moreover, it is also analyzed the given conditions to work, which have many complications from the safety of these workers to the guarantee of who will be able to raise a satisfactory income. All these concerns are also relevant when creating sustainable smart cities that favor the use of bikes.

3.3. Bike Sharing

The adoption of bikes as an effective transportation mean does not only depend on the availability of safe bike paths, but also on services that make the use of bikes as pervasive as possible. Generally speaking, this goal can be achieved if bikes are easily accessible, even if the accessed bikes belong to someone else. In order to promote the use of such types of bikes, bike-sharing public services and specialized apps started to be created all over the world, bringing an important boost for smart cycling.

Public Bike Systems (PBS), or simply bike-sharing systems, have been strongly promoted in recent years. This type of system, which has existed for decades but exploiting different supportive technologies, is becoming more popular today due to greater incentives to adopt more sustainable and healthy transportation [11]. Additionally, the wide dissemination of smartphones has also created a common platform for interactions between the users and the public bike systems, further supporting this type of service.

The idea behind the existence of bike sharing systems consists of making bikes available to be used for any purpose without compromising ownership, defining a new mobility service that is acquired only when and for as long as necessary [11]. In fact, the actual use of the shared bikes is not a concern of the systems, since they may be used for mobility efficiency but also for leisure. Figure 4 presents an example of a bike-sharing station in a large city.



Figure 4. A bike-sharing platform in a Brazilian city. Source: Tembici.

Usually, bike-sharing systems are based on a well-defined structure exploiting the use of a stock of robust and low-maintenance bicycles integrated in a network of parking stations. Such stations have space to store 10 to 100 bicycles in an automated way, using stations known as "docks" that are supported by some station control unit [52]. Thus, the registered users through mobile applications can take any bike at any station, returning it at the end of their path in a network of virtual or physical stations.

Many works have proposed promising solutions for efficient bike-sharing systems based on docks. In [53] a case study was conducted based on the "OV-fiets", a bike-sharing system with docks launched in the Netherlands in 2003. It provides thousands of bikes in hundreds of docks close to railway stations and urban public transport stops, promoting first and/or last mile trips. Also in the Netherlands, a bicycle-lease system is available, referred as the Swapfiets [54]. Founded in 2014, it allows users to rent bikes for a day and pick them up at a physical station, represented by stores rather than docks. This way, users get different options to use bikes for mobility, but the reality in countries as the Netherlands is far away from most of the low-income countries.

Another study focused on docked bike-sharing system is present in [55]. It was based on the quantitative analysis of some data related to trips made on Divvy, a Chicago platform created in 2013 with 300 initial stations and about 3000 bicycles. This data is related to information such as source and destination stations, duration of travel and type of platform server. Then, important decisions can be made when such data is available for a city.

Unlike bike-sharing systems with the use of docks, another model of PBS has been widely used, the "dockless". This is a new bike sharing service that does not have a parking network concept in its structure, allowing users to freely park the rented bike almost anywhere. This is different from the docked model, which determines parking stations for the bikes [56]. Among the benefits of such services, it is expected an important reduction of the deployment costs of the system, which is now strongly based on smartphone apps. Additionally, users acquire some level of flexibility when taking and returning bikes, which ultimately benefit the use of bikes for urban mobility.

Some works have proposed optimizations for dockless bike-sharing systems in recent years. In [54], a case study was developed using "Mobike" as an example of a dockless bike-sharing system. That application was launched in 2017 using shared smart bikes that can be parked in the areas defined by the company. These bikes use an IoT module with GPS and embedded wireless communication to allow users to find bikes in the app and use them. Following this trend, authors in [57] investigated this concept of smart bikes in Singapore. They considered "Ofo" as a PBS platform, which has been active in China since 2015. Such bike platform is focused on the IoT-based bike-sharing paradigm, allowing users to find bicycles in the app through an integrated sensor module, unlocking the chosen bike by reading a QRcode and starting using it. Actually, this bike-sharing model has rapidly spread as a viable solution.

Another way to unlock bikes that are inserted into a dockless bike-sharing system is through Bluetooth communication between a bike and the cyclist's smartphone. This type of authentication has also the potential to become quite popular. In [58], a dockless bike-sharing system is described, an initiative to use Bluetooth to unlock bikes in Poland.

Regardless of the type of the employed bike sharing system, it is highly expected a series of related benefits when supporting wider uses of bikes. In first place, when the barriers of ownership are removed, bikes can be considered as a highly available and practical transportation alternative. Actually, since bike parking may be an issue in large cities, it may discourage the adoption of bikes for some routes, demanding new solutions. Secondly, the acquisition and maintenance costs for bike owners may be prohibitive in some cases. In fact, when bike sharing systems become more present in our cities, governments could provide vouchers to stimulate even more the adoption of bikes for transportation, enhancing the construction of a smart cycling atmosphere.

4. Bike as a Platform: The IoT Revolution

The Internet of Things paradigm is centered on technological developments that have produced affordable electronic miniaturized components with reasonable processing power and reduced energy consumption [59]. Such components can then be exploited to add control and communication capabilities to virtually anything present in our daily lives [60]. This way, bikes can be equipped with sensing and processing devices, which would allow dynamic transmission and reception of crucial information to support new mobility optimization services. Moreover, bike paths, parking spots, trees, electric poles and even traffic lights can be endowed with IoT technologies to support smart cycling. Since the major objective of achieving a broader use of bikes still has many obstacles to deal with, such as traffic accidents involving cyclists and urban violence [39], the advent of IoT technologies can bring substantial improvements toward more sustainable cities supported by bikes.

The IoT principles and technologies have been successfully applied in multiple cases in the context of smart cities, bringing important contributions to improve the quality of life of the inhabitants [61]. Actually, the developments in different areas such as networks (4G, 5G, ZigBee, LoRA, RFID, etc.) [62], affordable embedded electronics [59] and computing techniques targeted at large amounts of data [63] have been crucial factors to support disruptive IoT services. In fact, the development of such IoT landscape, with the physical world being connected to digital platforms through sensors and actuators, can further enhance the adoption of bikes for active mobility, while also benefiting other areas for the construction of safer, sustainable and more resilient cities.

When concerning modern cities, many elements may interconnect to compose these big living organisms [64]. Mobility, health, security and sustainability are some of those elements, directly related to the perceived quality of life. So, the way bikes are inserted into the influence of such elements is of paramount importance, putting IoT-based smart cycling in a prominent place. Bikes fitted with sensors can act as monitoring devices for the riders, providing not only data about speed and traveled distances, but also about the health of the cyclists [60]. Additionally, since bikes can be connected to provide continuous data for storage and processing, a network of bike-sensors can be created, gathering data about the city and the environment around. Among the expected data to be monitored, sensors can detect air and noise pollution, temperature, atmospheric pressure, UV radiation and many other environmental variables.

Therefore, endowing bikes with hardware, sensing and communication capabilities is sparkling a new transformation for the maturation of smart cycling, since bikes can now be seen as active connected elements of a city for processing, transmission and reception of continuous data. Such transformation is expected to be a new incentive for the adoption of bikes, potentially attracting more interest from private organizations and governments [65]. For the known challenges when trying to deeply embrace bikes as an effective mobility alternative, IoT bikes arise to support new solutions, potentially reducing the gaps between the ideal world and the current urban realities.

Figure 5 presents a generic schema of IoT-enabled bikes: sensors, processing units, GPS receivers, networking cards and batteries are some usually expected elements for them.

The next sections will address some recent IoT-based developments towards the maturation of smart cycling.

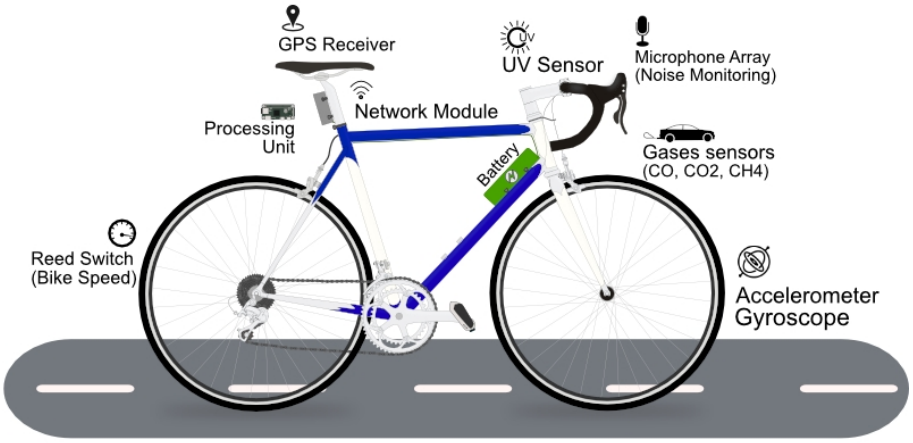


Figure 5. A generic schema when creating bikes in the IoT era.

4.1. Sustainability and Environmental Monitoring

When applying the concepts of IoT in the context of bikes, it is possible to develop new solutions that can expand the possibilities when concerning urban mobility. For example, among recent solutions in this sense, bike sharing has became possible with the dissemination of smartphones, but it is the IoT revolution that can further enhance the benefits of this service. Actually, bikes are great "last mile" solutions for mobility because they are affordable and can reach places that public transports can not [66]. Thus, if intelligent bikes are everywhere, the possibilities are tremendous [67].

The use of sensors, actuators and GPS receivers can allow bikes to perceive their environment, collecting important information [68]. Since a sensor is capable to retrieve data about some particular physical variable, such as temperature, pressure, humidity and luminosity, a bike becomes a mobile monitoring station. In this scenario, with mobile bikes gathering data from different parts of a city, a lot of important information can be extracted, supporting multiple urban services. In fact, the construction of smart cities demands the processing of data from different sources; since bikes can be used as a distributed data source, with complex mobility patterns, this group of data can support a new class of applications [5,18].

Some recent works have proposed the use of sensors attached to bikes for different types of monitoring. In [69], authors attached a camera to a bike to allow visual data processing of the road. Images are captured by bikes and transmitted toward the Cloud. Then, exploiting deep learning techniques, the quality of the road is identified, potentially supporting the evaluation of bike paths. Still considering the quality of the used roads, the work in [39] exploits data from sensor devices attached to bikes to evaluate the quality of bike paths, assigning quality levels based on Fuzzy logic rules. The idea in [39] is to balance different data related to the quality of the bike paths, which may even be useful to support route planning applications. For the work in [70], sensors are attached to bikes in order to allow the monitoring of the air quality, using for that smartphones to transmit the collected data. In all these works, sensors are attached to bikes to allow the monitoring of environmental variables or to collect images of the bike paths, enlarging the perceptions about the cities.

Generally speaking, environmental monitoring is an important activity to support sustainability. In fact, to achieve the sustainability of a system, it is necessary to make use of resources in a way that guarantees the continuity of this system in the long term. By monitoring environmental resources, it is possible to determine objectively if their use is being made in order to guarantee subsistence or if it is affecting the balance of the ecosystem. Therefore, environmental monitoring based on IoT bikes can play an important role in this scenario.

In [71], authors defined a generic architecture to monitor any type of environmental variable in a flexible way. Different types of sensors can be attached to bikes, which exploit a conventional multi-tier IoT architecture that separates sensing, processing and data delivery functions. Such flexible solutions can be largely adopted, specially when applying open-source hardware platforms [59,72].

Among the main concerns when performing environmental monitoring, pollution and air quality are top priorities. The issue of air quality is fundamental since the use of vehicles, which burn fossil fuels as an energy source, ends up emitting large amounts of harmful gases, including CO_2 and heavy particulates. Actually, since bikes do not cause pollution, they can be naturally equipped with pollution sensors, without affecting data collection. Thus, in order to monitor the emission of polluting gases into the atmosphere, several studies were developed in which the authors used sensors attached to bicycles to build a cheap and efficient network [73–76]. This should still remain a major concern for bike-centric environmental monitoring.

Likewise, it is possible to use several types of sensors to monitor a variety of environmental variables, thus allowing to detect emergencies such as fires, accidents, floods, among others [77]. By using these sensors in conjunction with bicycles, the measurement range is increased by using crowd-sourcing strategies to collect, process and analyze a large set of geolocalized historical data.

Table 4 summarizes recent works developed around environmental monitoring based on bikes.

Table 4. Monitoring of environmental variables exploiting bikes.

Approach	Year	Application	Sensed Data
Vagnoli et al. [76]	2014	Environment monitoring	Noise, humidity, temperature, air and road quality
Liu et al. [75]	2015	Air quality	Air pollution
Taniguchi et al. [78]	2015	Path quality	Pavement quality indicators
Wijerathne et al. [79]	2017	Path quality	Pavement quality indicators
Zhao et al. [80]	2017	Path quality	Pavement quality indicators, bike speed
Corno et al. [73]	2017	Environment monitoring	Temperature, humidity, pressure
Grama et al. [81]	2018	Environment monitoring	Multiple scalar data
Shen et al. [74]	2019	Environment monitoring	Multiple scalar data
Katto et al. [69]	2019	Path quality	Images
Quintero et al. [82]	2019	Noise level	Audio (noise) sensed data
Oliveira et al. [71]	2020	Monitoring of any variable	Scalar and multimedia data

In order to achieve statistically significant monitoring levels, a vast network of bicycles may be required, with sufficient adoption by the population. Actually, since the cyclists must feel safe when traveling, the ability to measure the quality and safety of the cycle paths is important. However, in large cities, the ability to monitor bike paths may be expensive, due to the area that must be covered, which in turn makes it difficult to manage and create policies that prioritize the development of this sector. Nevertheless, important steps have already been taken in this direction.

4.2. Promoting Health through Connected Bikes

Cycling is a well-known physical activity that has many health benefits for cyclists. Among them, cardio-respiratory fitness and reduced risk of developing diseases such as morbid obesity are some few examples [83]. Even in the cases when cyclists are exposed to harmful air pollution conditions—as discussed in the last section—the benefits of cycling may overlap the problems that inhaling polluted air can cause, excepting on extreme conditions of pollutants concentrations [84]. Promoting health habits by the use of bikes is a trending topic.

It is common among those who practice cycling as an exercise to monitor their activity in order to measure their progresses. Some cyclists usually make use of wearable devices like smartwatches or smartbands together with smartphones to measure vital

signs, traveled distance and the amount of time taken to complete the ride. Although already benefiting, such configuration can be considerably enhanced when IoT is exploited, turning bikes into sensing and processing stations. For the new generation of smart cycling solutions being created, health monitoring and assistance may become a pervasive service.

Some works have already proposed the use of sensors attached directly into bikes to make health-related measurements. In [85], multiple sensors are used to measure the heart rate of the cyclist, traveled distance and the speed of the bicycle. Information is gathered and processed by an Arduino board, allowing combination of the retrieved data. For [86], data of the cyclist in terms of health condition and cyclist's performance are provided by sensors, being available for processing. That approach uses a heart rate sensor and a pulse oximetry sensor (to measure the oxygen saturation inside the cyclist's body), besides sensors directly attached to the bike. In both cases, the wearable sensors can directly connect to any processing unit (e.g., a specific hardware board or a smartphone) in order to make sensed data available, which is a common approach when employing wearable sensors [87].

In addition to the use of sensors to monitor the cyclist's vital and health signs, other sensors such as accelerometers and gyroscopes can be used to detect falls and other types of accidents and then trigger emergency services as in the Accident Detection System proposed in [88]. In parallel, some authors have proposed the development of a system capable of preventing accidents instead of just detecting them, which favors preventive actions over responsive ones. The work developed in [89] proposed a system similar to the direction arrows already used in motor vehicles such as cars, motorcycles and buses to indicate the intention to perform a conversion to some direction, in addition to using a sonar type sensor to assess whether it is safe or not for the cyclist to perform a maneuver.

4.3. Internet of Bikes

The use of sensors, actuators and processing units can put smart cycling in a prominent place, providing and consuming multiple data in different scenarios. However, while the processing of sensed data retrieved from bikes can support useful applications, the breakthrough is expected when bikes communicate with each other. In short, connected bikes will be able to transmit and receive data dynamically, for example adjusting routes and avoiding risky areas. With connectable bikes, we take a bigger step toward sustainable and smart cities.

The idea of the Internet of Bikes (IoB) is taking shape through incremental developments in the area, with promising solutions emerging in recent years. An obvious movement in this direction has been done when creating bike-sharing systems, since connected bikes that does not depend on the cyclists' smartphones are safer and better monitored [66]. For that, some works have discussed communication issues that could impact such services. In [90], a protocol is proposed to support bike-centric communications target at bike sharing, assuming that IoT bikes will have inherent processing, memory and networking constraints. The proposed delay-tolerant protocol is based on the store-carry-and-forward principle, which allows temporal storage of packets by the network in order to better adapt to the constraints and mobility pattern of the bikes. Variations of this protocol are discussed in [91].

Other concerns may arise when connecting bikes. If all elements associated to the urban mobility are connected and integrated, much better decisions can be taken in a real-time basis. Actually, the evolution of autonomous vehicles in recent years has raised questions about safety in general, both for the people inside the vehicles and for those around them. In this context, bikes will often share space with these vehicles, but an IoT bike can dynamically respond to smart vehicles, potentially reducing accidents and optimizing traffic. It has been observed the importance of addressing the challenges of this dynamic scenario in order to ensure the safety and well-being of the cyclists, who are on the weaker side of this scale. In [92], a survey was conducted about the implications of autonomous vehicles in relation to bicycles and on the policies that must be adopted

to guarantee a harmonious coexistence between these transportation means. For an IoT world, such discussions should remain relevant.

Next section will further address some of the most important issues related to e-bikes and the new generation of connected smart cycling, highlighting promising development trends in this area.

5. The Rise of E-Bikes

From New York to Bangkok to Natal, urban bikes usage is on a steady rise. As citizens of the world's greatest cities seek alternative transportation methods—less expensive and less harmful than cars or public transit systems—the popularity and importance of bikes has become clearer and more urgent [93]. In this propitious scenario, a new trend is becoming quite popular, giving an additional boost for smart cycling. This new trend has been driven by e-bikes.

An electrical bicycle (e-bike) has a motor assisted pedal with a rechargeable battery, facilitating its use as a daily transportation option. Similarly, electrical scooters are also based on an assistant motor connected to a rechargeable battery, being also referred as e-bikes for simplification. In practical means, less effort is required in both cases, making their use more comfortable and accessible for elderly and disabled people. In general, the same innovations that can foster smart cycling for traditional bikes are also available for e-bikes, since the same cycling challenges are faced by them.

Many bike technologies could positively impact the future of personal travel, but e-bikes stand out from the crowd. One significant factor is that batteries have made it possible for e-bikes to work as efficiently as conventional bicycles [94]. Many people prefer e-bikes over other forms of transportation because they help to reduce the physical effort required to pedal but still provide the health benefits of exercise [95]. And this can be a decisive factor when fostering smart cycling initiatives.

5.1. The E-Bike Market

E-bikes have spread, especially among the most industrialized countries. As illustrated in Figure 6, the market for electric bicycles (bicycles, tricycles and quadricycles, with pedal assistance, with an auxiliary electric motor with a continuous rated power less than or equal to 250 W) within the European Union, both for imports and exports, was growing before the COVID-19 Pandemic. In 2019, these trades surpassed the mark of 2 million units each one. With regard to exchanges between EU and the rest of the world, they are less significant, especially in relation to exports, showing the potential of the consumer and e-bike producer market in the region. But as previously explained, it does not represent benefits only, but important challenges for urban mobility.

Generally speaking, the ubiquity of power sockets—and the relative ease and quickness with which e-bike batteries can be charged—is possibly the most appealing predictor preferring their gradual adoption [96]. A typical e-bike can be recharged in a garage, at the office, or in the middle of a campground [97]. No longer it needs to stress about running out of charge—not to mention, the portability factor is convenient.

Besides contributions related to personal mobility in urban areas, e-bikes can also bring other promising benefits. The use of electric cargo bikes might yet become an inevitable solution for last-mile delivery in cities. They have zero carbon emissions and occupy less road space than cars when in use or parked [98]. Logistics companies can collect comparative data to determine when using e-cargo bikes will improve delivery times and reduce costs. Actually, the perspectives for an increasing use of e-bikes are tremendous.

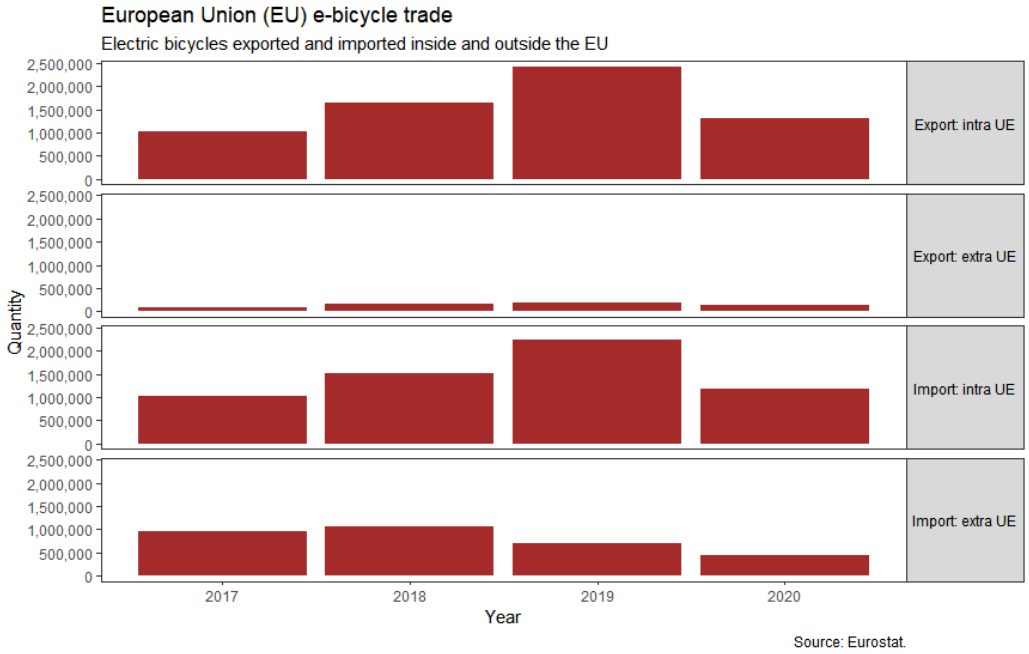


Figure 6. EU trade in electric bicycles: 2017–2020. Source: Eurostat.

5.2. Connecting E-Bikes

It is already expected that e-bikes will become an important element in urban mobility, although its adoption has not been uniform around the world. In this scenario, a parallel trend is the connection of such transportation means. For the mobility challenges in modern cities, e-bikes have to be online [99,100].

As aforementioned, there are many services that can be associated with bikes, exploiting smartphones or IoT technologies. Typically, wireless connectivity has an essential role in order to send different types of data (e.g., workout, geolocalization, health parameters) for different types of applications [101]. Actually, with the miniaturization of electronics, wireless communications technologies have enabled the integration of all components that make up the smart cycling ecosystem (bikes, sensors, users and things) [86]. In this context, we believe that e-bikes are naturally prone to be wirelessly connected, supporting specific applications or a broader construction of smart cities.

Figure 7 summarizes a sweeping panorama for this reality highlighting intra-network and inter-network aspects. Intra-network communication is exemplified by the embedded instrumentation installed in the bikes, called Bike-to-Sensor communication (B2S). On the other hand, the latter encompasses a broad perspective, connecting bikes to users (B2P), bikes to bikes (B2B), and bikes to smart things (B2X). Conventional IoT network technologies, such as WPANs (Wireless Personal Area Networks), whose solutions are variations developed by the IEEE 802.15 workgroup, and the new trends over Low Power Wide Area Networking (LPWAN), have also essential roles in the connecting bikes realm [102,103]. When in synergy, this new ecosystem of communication technologies fosters the creation of a new research area entitled BANETs (Bike Ad hoc Networks) [104].

BANETs is an emerging fruitful research area with promising contributions in literature. When considering communication between bikes, B2B paradigm is viewed as a standard where WPAN and LPWAN networks are widely adopted. Authors in [105,106] evaluate a B2B communication when considering LoRa, LoRaWAN, Narrow Band-Internet of Things (NB-IoT), and XBee modules. Results indicated a reliable bi-directional communication for real-time tracking. Another evaluation has shown that the link performance in a typical B2B communication depend tightly on whether bikes are approaching or moving away, rather than on whether it is in front or behind of the other [107]. Challenges in B2B are also discussed in [108,109], where periodic beacon messages were investigated

under vulnerability to malicious jamming attacks and dependability issues. Protection of individual privacy in B2B is also a relevant topic, as can be investigated in [110,111].

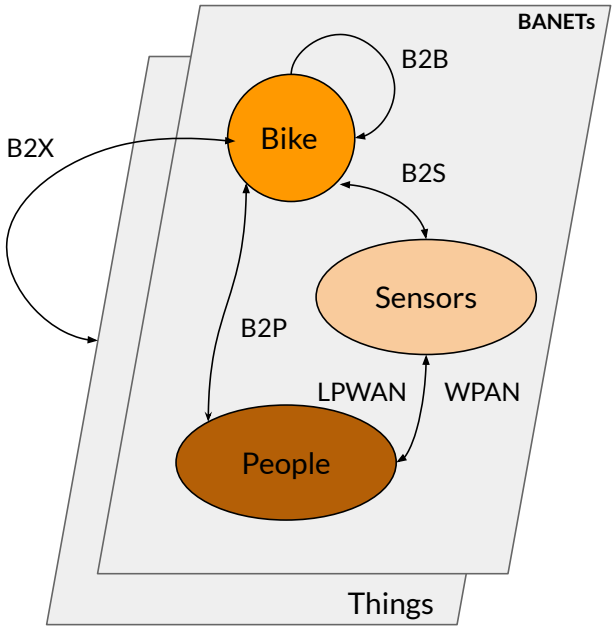


Figure 7. Technologies for connecting bikes.

B2P is another important branch in the context of BANETs. In general, communications between bikes and users are focused on setup configuration, check-in, authentication, and monitoring purposes. WPAN technologies such as Bluetooth and NFC are widely adopted. However, the use of mobile networks and local wireless networks have been very widespread too [112]. Authors in [113,114] investigated B2P for monitoring the localization of bikes. Technologies of communications were used as checkpoint to improve the localization of bikes together with GPS signals. Mobile networks have been also used as gateway in order to sink the information used for monitoring applications [115,116]. Authors in [117,118] developed assistance systems to provide sensitive information needed to avoid critical situations during cycling. Beyond of safety purposes, security is a key element when considering B2P. Authentication mechanisms based on hybrid communication technologies (Wi-Fi, NFC) has been proposed in [119,120], but other research works should still address this issue.

B2S communication is a specific class of BANETs that consists of the exchange of information between a bike and any electronic device that may be embedded in the bike itself. The main focus is related to development of basic instrumentation and communication interfaces (wireless and wired) [121,122]. Lastly, B2X encompasses a communication scenario of the "bike to everything". It is a futurist scenario where all things and smart objects have ubiquitous communication with bikes [104]. Emerging communication protocols such as 5G, LoRa, and LoRaWAN arises with candidates to be adopted as *de facto* solutions [123]. Challenges and opportunities are related to interoperability between different protocols and new applications, which data stream is a new trend as is the case of multimedia stream applications [124].

Table 5 summarizes the main discussion and challenges related to BANETs, enumerating communication technologies and related topics.

Table 5. Summary of BANETs challenges.

BANETs	Communication Technology	Research Topics
B2B	LoRa, LoRaWAN, NB-IoT, IEEE 802.11x, IEEE 802.15.4x	Performance, Simulation, Security, Privacy, Dependability
B2P	Bluetooth, NFC, IEEE 802.11x, Mobile Network	Localization, Authentication, Safety
B2S	Bluetooth, Legacy Wired Technologies	Testbed, Instrumentation
B2X	5G, LoRa, LoRaWAN	Interoperability, Multimedia Stream Applications

6. Open Challenges and Research Directions

This article has discussed the main research areas and development initiatives for smart cycling, aimed at sustainability and mobility efficiency in urban areas. Important research works were discussed, highlighting challenges and promising solutions. After the presented discussions, this section indicates some promising research directions, pointing out open challenges to be addressed in the coming years.

6.1. The Foundations for Sustainable Mobility

Recently, a lot of initiates are emerging to discuss and even to promote sustainable mobility, creating the foundations to consolidate smart cycling. According to the 2030 Agenda for Sustainable Development of the United Nations (UN), the Goal 11 aims at making cities "inclusive, safe, resilient and sustainable", considering an urbanized world that will still be growing during the coming decades. Since 2007, most people live in urban areas, with the expected formation of large urban agglomerations on all continents.

The Goal 11 also contemplates access to sustainable transport systems, especially for vulnerable groups. At the same time that it represents an alternative and a sustainable form of transport, the use of bikes for urban mobility, in particular, characterizes cyclists as one of the most fragile in road traffic. According to the World Health Organization (WHO), the group of motorcyclists, pedestrians and cyclists account for more than half of road traffic deaths. Based on 2018 data, it is estimated that the number of cyclist deaths worldwide exceeds 40,000 each year, an alarming mark that surpasses 100 deaths per day [125].

This way, the mobility issues concerning cyclists will sill represent an important source of challenges to be addressed by future works, comprising not only mobility efficiency but also reduction in injuries and deaths. And this complex scenario should indeed attract much of the public funding for research and development in the next years.

The adoption of e-bikes also brings important challenges. For example, risk behaviors as illegal occupation of motor vehicle lanes and speeding [126,127] are prevalent among e-cyclists, as well as greater chances of accidents that could result in severe and multiple injuries [126,128]. On the other hand, e-bikes are comfortable and ecological [126], require low effort to reach proper speed and climb up hills, and travel time tends to be shorter [129] compared to travel using conventional bikes. This way, e-bikes should be considered as a transportation alternative that came to stay.

Although high income countries have more efficient transport systems compared to low and middle income countries, they face other challenges to be overcome in order to guarantee their citizens the right to safely cycle. Regarding the demographic transition, the most industrialized countries experience an acute process of population aging. In fact, it may be a window of opportunity in terms of mobility planning to deal with a reduced contingent of young people, since they tend to be more involved in road traffic accidents. On the other hand, a huge elderly population has its own specificities in terms of urban mobility that need to be taken into account. For example, despite the benefits of cycling for elderly people, as physical and mental health gains, the increased risks of injuries and deaths among cyclists at advanced ages have been documented in literature [130–132].

Even considering that the benefits of bikes for enhanced mobility efficiency with zero emissions are quite obvious, the reality is not very encouraging. In the beginning of the 2020 decade, combustion vehicles were still the predominant transportation option

in large cities, even with alarming levels of air and noise pollution being reported every year. However, since the collective social mindset is centered on traditional combustion vehicles, a deep change in our mobility patterns is still a distant dream. Nevertheless, such challenges have also fostered important innovations from both public and private organizations, with many promising solutions coming to the scene.

6.2. Promising Technological Trends

In addition to electrification, technology is offering a myriad of others bike-friendly features to improve the riding experience for everyone [133–135]. Many cities find that the cost of traffic due to congestion keeps increasing, with average travel speeds getting slower each year. This means that bikes, perhaps most notably e-bikes, are becoming the most agile solution for urban areas [136]. For example, cyclists can share their commutes for a cloud-based platform that allows others to plan their commute from a crowd-sourcing perspective [137]. Bikers can also found in this crowd-sourced environment information about the number of calories burned by cycling and the amount of pollution that is not emitted or green lane completed [138]. These solutions are only possible thanks to the wireless connectivity instrumented into the bikes, making a bridge between all bikers and the cloud platform. In a very realistic glimpse of the future, wirelessly connected bikes will be the mainstream cycling resource.

The growth of cycling is related to the widespread use of technological innovations. These technologies include a horizontal ecosystem of solutions incorporating data-driven analytics perspective, embedded application design, holistic urban planning tools, 3D printed parts, electrification, and wireless connectivity [139,140]. Each of these technologies developed by different players is working together to create an array of biking advancements. In this scenario, wireless connectivity emerges as a principal actor, aggregating the transmission of raw and processed data generated by the various technologies and mainly connecting the bikers.

The envisioned developments in this area are almost limitless. From helmets that can communicate with cars to smart openers for garages, wireless technologies are expected to make cycling safer [124]. Helmet-integrated lights can be used by cyclists who are not able to signal their turns in other ways. Such helmet could be a high-end solution designed to integrate the lights into the helmet safely [141,142]. Other solutions might use audio integration, which would allow the cyclist to communicate with other bike riders and pedestrians without taking a hand off the handlebars [68,143].

Particularly for accidents prevention, the use of IoT technologies can be highly helpful, providing important data to process risk zones and signalize dangerous behaviors. Such IoT revolution for smart cycling will open other promising paths concerning what connected bikes can do. Besides the communication possibilities when bikes interact with other devices, the processing capabilities that is being added to bikes are already allowing the processing of artificial intelligence algorithms. Actually, with the development of off-the-shelf miniaturized electronic devices with sufficient processing capabilities, bikes will be able to directly interact with the environment, learning how to better behave concerning a set of bike paths and neighborhoods. Particularly, machine learning algorithms can be embedded into miniaturized hardware platforms, defining the concept of TinyML, which should be more often considered in the development of smart bikes [144–146]. Then, exploiting theses resources, algorithms for accidents prevention could be developed to be executed directly on bikes, for example emitting sound alerts when an accident is about to happen. Overall, this should be an important research trend that may bring significant results for smart cycling.

Finally, when concerning technological trends for smart cycling, we believe that the integration of e-bikes solutions with smartphones, sensors attached to the bikes and wearable devices will be leveraged to enhance the safety, efficiency and mobility experience of the cyclists. Such integration should be deeper exploited in future research.

6.3. Developing Smart Cycling Solutions

The so-called technological wonders that we have experienced in the last couple of decades are already impacting our lives in many unexpected ways. Pervasive social medias, automated houses, cleaning robots, computer-assisted vehicles, smart gadgets and many more resources are increasingly and surprisingly present in the daily lives of a growing number of people, laying the foundations of our digital world. In this vibrating and thrilling atmosphere, smart cycling is emerging as a fundamental service to be provided by urban spaces that are committed to good quality of life indicators. Nevertheless, since many challenges still remain when trying to switch the mobility paradigm from traditional combustion vehicles to efficient multi-modal services supported by bikes, substantial research and development efforts are still required.

As mentioned before, a broader adoption of bikes would demand a transformation of the cities landscape, with the granting of higher relevance to bikes over traditional vehicles. In parallel, there is a urgent need for growing investments in high-capacity public transportation systems, which also creates a favorable environment for bikes. In fact, more than one century of public policies have majorly favored the combustion engine vehicles over other transportation means, and a significant change from automobility to cyclomobility is still not in the horizon. Hence, since such transformation would require decades or even centuries, research and development efforts should be focused on improving the safety and experience of cyclists when they move, smoothly reducing the number of traditional drivers while stimulating an increasing in the number of active bike users. In this sense, the development of new apps and IoT devices to support different uses of bikes should remain an important trend, further supporting urban cycling.

In large and mega cities, expressive use of bikes for transportation reasons may be prohibitive in many cases, specially due to travel distances. For this scenario, some works have discussed the growing benefits of bike-sharing approaches, which ideally allows easy and affordable use of shared bikes for routes not covered by high capacity transports such as railway systems [17,112]. For the next years, this trend should still be important to support sustainable smart cycling, since new business models should still emerge and mature. As an example, with the popularization of bike-sharing applications, more private companies will see the potential of adverting when more bikes move on a city. With additional financial support to expand the number of bikes to be shared, the number of uncovered areas will naturally shrink, further supporting the adoption of alternative transportation options.

The development of new apps to support smart cycling should follow the availability of new hardware platforms. With the releasing of more powerful and affordable smartphones and wearable gadgets, new groups of applications may be created to exploit new sets of embedded sensors and available databases. In this sense, it is also expected that the adoption of communication technologies with higher bandwidth and lower transmissions delays, such as the 5G standard, may also boost the development of apps targeted at smart cycling [93,147].

Besides the use of smartphones and wearable gadgets to support new bike-oriented services, other important development and research trend is focused on the IoT paradigm. Since a bike can be equipped with any number of sensors and processing units, allowing the use of bikes as an IoT platform, new types of information can be gathered and processed. In general, it is natural to expect that such units will not only support already known applications such as delivery and bike-sharing, but they may also foster new applications that are not possible today. For example, while sensors-enabled bikes may be used to assess the quality of bike paths [39,71], new applications could exploit such sensors to go even further, transmitting and receiving information in real-time. In such scenario composed of connected (e-)bikes, rescue operations could benefit from distributed information about the movement of people and the surrounding conditions, potentially guiding rescue teams. Additionally, online information could also benefit mobility planning as well, for example adjusting the operation of traffic lights according to the current flows of cyclists (and not only the traffic conditions concerning combustion vehicles). When bikes are nodes of a

giant network, the possibilities are enormous and the concept of Internet of Bikes (IoB) becomes very appropriated.

Finally, when we come to the perception of smart cities, all connected elements are important to provide valuable information to this macro system [77,148]. However, mobile elements will be a bit more relevant since they can provide information from multiple areas, dynamically. When such mobile information is combined with people-centric data, such as huge amount of information provided by wearable sensors and also social media [17,149,150], the possibilities in terms of disruptive services are beyond imagination. But such possibilities will require robust support by the digital infrastructure of the smart cities, which will need to handle massive amounts of data per second. For the giant expected transformations in next decades, efficient communication and data storage infrastructure are fundamental requirements.

6.4. The Post-Pandemic World

The dramatic events related to the COVID-19 Pandemic have deeply changed some perspectives about how smart cities should be created and managed [151]. Although there are already some research works assessing and trying to adapt the use of bikes to the post-pandemic world [49,152,153], the construction of smart cycling initiatives should be strongly influenced by the health and social measures adopted to restrict the surge and spread of outbreaks. In fact, new highly contagious diseases may surge anytime and anywhere, and it is natural to expect that new solutions will be already adapted to eventual restriction measures.

It is important to note that the COVID-19 Pandemic impacted circulation in large urban centers and with special attention to the use of bikes for commuting. After the first measures of social distancing and further lockdown, which suspended activities considered non-essential to trying to contain the spread of this coronavirus, the road traffic in large cities was never the same. The restrictions imposed on the movement of people had important effects such as the reduction of road traffic accidents [154,155] and air and noise pollution [156,157].

In this context in which the formation of agglomerations should be avoided, bike commuting is considered an important environment and social distancing-friendly solution [153]. In this line, there was a considerable increase in the circulation of cyclists during the pandemic, whether for leisure time or work, as well as an important growth of the bike delivery services market [31].

This increase in bike commuters during the pandemic may be contributing to important changes in the habits of the population in large urban centers, concerning practical aspects of daily life, such as greater adherence to purchases by bike delivery, as well as greater use of bikes, at least when traveling for short distances. Even with the prospect of a massive vaccination against COVID-19 that might put the pandemic under control, it is possible that these behavior changes will last, which will require governments to take more concrete actions to offer safe and pleasant conditions for cyclomobility in large urban centers.

Actually, for a world permeated by large and mega cities, the control of outbreaks will be centered on urban spaces, with mobility as a key element [77]. Henceforth, the new generations of bikes and smart cycling solutions should be prepared to deal with their growing impacts on our society. In an optimistic but also realistic glimpse of the future, the next pandemic may be avoided by smart and interconnected bikes.

7. Conclusions

The world is in a continuous changing process, struggling to adapt to old and new challenges in different aspects of our lives. With the strong urbanization in recent decades, mobility has become an important issue, pushing governments to find new solutions in this area. As surveyed in this article, bikes can be an important ally of large and mega cities, increasing mobility efficiency, promoting health habits and reducing air pollution levels.

Since the technologies are already providing the resources for that, the society should step in and makes its part.

There are many goals when concerning the improvement of the perceived quality of life in cities. Among them, there is an urgent need for sustainable solutions in urban areas, with varying objectives and challenges. Actually, although the concept of sustainability can be too broad, the urgency around it is usually originated from a scarcity of resources and growing levels of pollution. Therefore, with more efficient management of the available resources and provided services to the inhabitants, sustainable cities can be created. In this promising scenario, sustainability is a core element when pursuing all expected optimizations of the urban spaces.

Although smart cycling is highly anticipated as an important element to achieve sustainable mobility, more research and developments are still required. The envisioned research directions in this survey are important indications of what need to be done and how cities should prepare themselves to embrace such developments. Overall, we expect that deep transformations should happen in this century, with bikes as core elements to promote sustainable, safer and more resilient cities.

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