An End-to-End Solution for Enabling Urban Cyclability: The B\textsc{ike}2\textsc{work} Experience

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Abstract—Mobility plays a fundamental role in modern cities. How citizens experience the city, access its core services, and participate in city life, strongly depends on its mobility organization and efficiency. The challenges that municipalities face are very ambitious: on the one hand, administrators must guarantee their citizens the right to mobility and to easily access local services; on the other hand, they need to minimize the economic, social, and environmental costs of the mobility system. Municipalities are increasingly facing problems of traffic congestion, road safety, energy dependency and air pollution, and therefore encouraging a shift towards sustainable mobility habits based on active mobility is of central importance. Active modes, such as cycling, should be particularly encouraged, especially for local recurrent journeys (i.e., home–to–school, home–to–work). In this context, addressing and mitigating commuter-generated traffic requires engaging public and private stakeholders through innovative and collaborative approaches that focus not only on supply (e.g., roads and vehicles) but also on transportation demand management. In this paper, we propose an end-to-end solution for enabling urban cyclability. It supports the companies’ Mobility Managers (MMs) acting on the promotion of active mobility for home-to-work commuting, helps the city administrators to understand the needed urban planning interventions, and motivates the citizens to sustainable mobility.

To evaluate the effectiveness of the proposed solution we developed two analyses: the first to accurately analyze the user experience and any behaviour change related to the B\textsc{ike}2\textsc{work} initiative, and the second to demonstrate how exploiting the collected data we can inform and possible guide the involved municipality (i.e., Ferrara, a city in Northern Italy) in improving the urban cyclability.

Index Terms—Sustainable mobility, active mobility, smart city, motivational systems, engagement, behaviour change.

I. INTRODUCTION

The traditional and car-centric transportation planning has not only significantly contributed to increasing greenhouse emissions but has also detrimentally influenced air quality, traffic congestion, fatalities, and road injuries \cite{1,2}. With the world facing a climate crisis, there is a need for a paradigmatic shift towards a more sustainable and active mobility \cite{3}. Sustaining and attaining significantly higher rates in cycling and walking as modes of transportation (also known as active mobility), and nudging people to walk and cycle more, represent one of the most powerful and significant instruments to achieve social goals and sustainability \cite{4}. Regrettably, infrastructures and incentives for promoting modes of transportation such as walking and cycling are significantly underfunded as compared to car-centric transportation planning and design \cite{5}. Urban cyclability is a wide notion that connects several elements to bicycle riding, depending on the research’s emphasis and interest \cite{6}. It is mostly used in transportation, urban planning, population health, and wellness \cite{7}. To drive the change in the mobility habits of people and to promote sustainable modes of transportation, an important role is played by the design and implementation of instruments that drive changes in individual behaviour. For example, collaboration with formal and social groups like sport clubs has proven to be effective in providing significant strategies for motivating the level of participation in programs related to behavioural change toward active and sustainable mobility \cite{8}. Practical guidance has been proven to be a significant inspiration and motivation for increasing the level of cycling, walking, and using public transport. Providing the target audience with the right kind of information such as the display of site-based data, and the promotion and organization of workshops to inform and train people on alternative and greener ways of travelling can significantly influence the mode or the choice of the mean of transportation \cite{9}. Furthermore, accessibility instruments such as the availability of timetables, and the use of advertisements and leaflets can significantly promote and encourage the public to adopt modes of active and sustainable transportation \cite{10}.

To promote active and sustainable mobility it is critical to analyze the effects of the decisions taken in support of this type of mobility and to evaluate the users’ experience. This can be achieved by monitoring the number of registered participants, identifying and profiling the most regular and active individuals, assessing the trips made and the modes of the trip, and analyzing their possible observed variation \cite{11}. Additionally, there is a significant need for systems that assess the levels of individuals who shift towards sustainable and active modes of transportation \cite{9,10}. Furthermore, activities like the modal split data, and the analysis of vehicles and people in terms of the saved vehicle kilometres, while a certain action is being performed, have also been observed to be a
satisfactory and acceptable method of survey and evaluation [9], [10].

In this paper, we present an end-to-end framework to promote a more sustainable home-to-work mobility, through the adoption of technological solutions together with the active involvement and engagement of companies and their employees. Mixing software solutions, economic incentives, data collection strategies and data analysis methodologies, we build a novel innovative, sustainable, and targeted framework to guide individuals toward a behavioural change. With the data collected through the user experience questionnaire, we show that the Bike2Work campaign significantly increased the use of bicycles for commuting from home to work. With the data collected by the Ferrara Play&Go mobile app we analyze the Bike2Work bicycles’ trajectories to understand how much a user travelled path diverges from the optimal one (i.e., shortest paths). Moreover, we assess how the street network’s safety level plays a role in the path selection of cyclists. Through the reported experience, we demonstrate how the solution proposed enables the understanding of the level of urban cyclability and helps the mobility (city) managers to derive the needed urban planning interventions.

A. Paper Structure

Starting from the background and motivations that led to the realization of our solution (see Section II), we present the Bike2Work objectives and the various steps that have been performed to engage both companies and employees (see Section III). We then continue by providing details on the technical implementation supporting its management and operations (see Section IV). We show how we support cities and local authorities to use the data coming from users’ experience and behaviour to identify weaknesses in the city they manage. We conclude the paper with the qualitative (see Section VI-A) and quantitative (see Section VI-B) analysis of the Bike2Work experiments and with some conclusions and future work (see Section VII).

II. BACKGROUND AND MOTIVATIONS

A. From Walkability to Urban Cyclability

Urban cyclability evolved from the notion of walkability, expanding the study to include all the active modes [12]. Cities that are ecologically sustainable, athletic, and socially viable rely heavily on bicycles [6]. By combining the concepts of walkability and urban cyclability, the idea of likeability was formed to assess the degree to which riding a bicycle is made easier [13]. For governments and other stakeholders interested in supporting sustainability goals in urban mobility [14], [15], [16], the development of urban mobility policies and standards has become a crucial subject of inquiry and action [12], [17]. With transportation accounting for nearly a third of energy usage in both the European Union (EU) and the United States (US), and “single-occupancy vehicle (SOV)” daily commute rates even now high, there are numerous barriers to reducing pollution and other personal, societal, and ecological costs involved with this mode of transportation [13]. Although there was little interest in the issue before the start of the decade, there have been various projects since the turn of the century to assess the quality of surroundings for active modes [12], [18]. Nonetheless, the great majority of them focus only on walking [19]. Instead, an essential element of new development agendas for future cities is based on the need to adopt and advance sustainable mobility strategies [20]. Such policies need to focus on making mobility affordable, accessible, and sustainable by enhancing walking, cycling and public transport services while reducing the impact of vehicular traffic at local and national levels.

B. Active Mobility Advantages

Research by the European Environmental Agency (EEA) shows that the transport sector is responsible for around a quarter of total greenhouse gas emissions in the EU (EEA, 2020). A recent report on the latest trends declared that current levels are unlikely to achieve 2030 targets, reinforcing the need to promote passive forms of emission reductions by reducing the need to rely on energy-intensive modes of travel. The number of cars in Europe has increased by more than 10% in less than ten years, with strong growth of traffic jams and rising CO2 emissions. To reduce these emissions and meet climate goals we need to drastically increase our efforts to reduce transport. As shown by previous research, active and shared mobility have proven to be a very relevant part of the solution. Bike sharing encourages citizens to cycle more or to start cycling again. Shared bike rides are often combined with public transport trips and offer an alternative for car use or even car ownership. The societal advantages of active and shared mobility are manifold: fewer car trips, more use of active and public transport, less CO2 emissions and pollution, and more valuable public spaces. There are also important individual advantages: people save time not having to look for parking, they are less frustrated not having to bother about administrative car issues, they live healthier through more active travels, and they can save a large amount of money (avoiding taxes, insurances, maintenance, parking fees). Nevertheless, the number of users embracing active mobility is still low: people are used to have their own car and it is hard to convince them to consider getting rid of it. The mental shift that fosters a behavioural change that eventually leads to a modal shift poses a tough challenge for both city planners and active mobility operators.

C. Encouraging cyclability

Mobility is likely to be a valuable application area as the impact on the environment, climate, and land use is beyond the current generation, given that it requires paradigm-shifting decisions at the level of individuals (i.e., behavioural change) and decision-makers (i.e., policies and the use of resources).
Thus, incentivizing citizens to be more engaged in sustainable mobility actions and changes is of paramount relevance to the success of the different Green Deal aspects because mobility behaviour, like many other behaviours, has a strong impact on the environment. Civic engagement that promotes ecological mobility can take different forms and may involve different populations. Each change may collectively bring a greater result. Technological solutions may facilitate some collective behavioural changes. However, it should not be forgotten that these changes start from individual changes. To achieve successful results, it is crucial to take into account all individuals in an inclusive approach. Sustainable mobility solutions have to be addressed according to the specific characteristics of the individuals, the institutions, the territories and the transport organizations.

To encourage cyclability, social characteristics can be viewed as a potential benefit particularly when it comes to inspiring change. Several persuasive principles that emerge around the social dimension have been established in the setting of behaviour change toward urban mobility. Social comparison, social facilitation, normative impact, social learning, competitiveness, and praise are examples of these concepts.

D. Quantify Urban Cyclability

Many researchers have developed indexes to assess specific aspects of the built environment that influence cycling behaviour and thoroughly quantify urban cyclability, namely the extent to which an environment is friendly for bicycling. Previous research dealing with the development of urban cyclability indices had to deal with challenges such as the time-consuming data gathering procedure, the balance between subjective and objective reasoning, the extraction of street-level data, and the standardization of spatial granularity. According to likeability literature studies, the historical progress of urban cyclability evaluation has indeed been driven by inventive applications of sophisticated new technology (i.e., street view imagery (SVI), computer vision (CV)).

III. Bike2Work: Objectives, Features and Management

Within the AIR-BREAK project, behaviour change and awareness raising campaigns have the aim to inform citizens’ and raise their awareness on the possibilities and advantages offered by the available sustainable mobility services and to encourage the adoption of different, more sustainable, mobility habits. Bike2Work is one of the initiatives in this direction with the goal to promote an approach to mobility oriented to workers able to support the company Mobility Manager in the promotion of sustainable mobility and transport demand management by analyzing the problems, needs and habits of workers, trying to orient them towards new habits of sustainable transport.

The overall objective of Bike2Work is to promote a more sustainable home-to-work mobility, contributing to the reduction of CO2 emissions.

The adoption of technological solutions alone cannot make transport more sustainable; to do so it is necessary to involve people and guide them towards a behavioural change. To achieve these goals, Bike2Work intends to engage companies with their employees to build new innovative, sustainable, and targeted solutions that can improve quality of life more effectively.

The specific objectives of this initiative are:

- To support workers in switching to sustainable mobility habits resulting in reduced CO2 emissions;
- To support public/private companies in the adoption of policies, initiatives, and the development of urban mobility plans;
- To increase the perception of corporate (ecological) Social Responsibility and improve Total Quality Management (TQM) within companies;
- To increase cooperation between different modes of transport and promote interconnection and interoperability between existing transport networks;
- To increase the attractiveness of sustainable transport modes through the implementation of different measures such as proposing new private mobility policies, promoting public transport, and pooling and sharing services.

To evaluate the overall Bike2Work objectives listed before, the city of Ferrara has been chosen. It is a medium-sized Italian city located between Bologna and Venice, along the Po river, with an overall number of inhabitants of 131,000 distributed in an area of 400 Km². The city has broad streets and numerous palaces dating from the Renaissance, when it hosted the court of the House of Este. Moreover, Ferrara is a pretty flat city where weather conditions are never particularly impactful.

The Bike2Work initiative was launched in May 2021 and it is still running. It is part of the sustainable mobility initiatives put in place from the Municipality of Ferrara to promote the use of bicycles for home-to-work trips by providing an economic incentive to employees of public or private companies.

Bike2Work provides incentives for sustainable mobility through an economic contribution for workers committed to using bicycles for home-to-work trips. Employees of participating companies are rewarded for their home-to-work trips by bike with economic incentives in their paychecks (0.20 € per Km, max 50 € per month, max 20 km per day). Mobility managers and employees are supported by a software platform and a mobile app, as described in Section IV-A and the overall campaign participation is supported by a specific life-cycle depicted in Figure. Each interested company provides (in STEP 01) the following information: (a) all the company data and (b) the list of Mobility Managers (MMs) with their related information. After that, in STEP 02 each company specifies the details of the headquarters participating in the Bike2Work campaign with the declaration of closure.

6 https://airbreakferrara.net/
7 https://www.comune.fe.it/
days (e.g., holidays). STEP 03 is dedicated to inserting the employee’s data that will be invited/engaged by the MM during STEP 04. In this phase, the MM sends an email to each participating employee. In this email each employee receives:

- The presentation of the campaign with the relative regulations and information regarding data processing and privacy;
- The instructions to perform the registration to the campaign and to download the software application needed to participate.

As soon as an employee accepts the invitation to participate to the Bike2Work campaign and the registration is done, s/he can start tracking the home–to–work and work–to–home bike journeys (STEP 05). Finally, STEP 06 is used to manage the employees’ performance and reward them with the corresponding amount.

IV. THE BIKE2WORK SOFTWARE SYSTEM

The life-cycle and all the features presented in the previous Section have been used to guide the implementation of the Play&Go Aziende (Companies) Framework. It is an innovative software solution that provides a console of data, information, recommendations, and simulations for MM to assess, also through what-if analysis, the environmental impact of employees’ commuting, to evaluate changes because of specific measures and actions, and to plan optimal and sustainable workers’ mobility strategies.

To achieve the identified objectives, Play&Go Aziende (Companies) provides:

- A **web console** - for the MM of the company to manage the necessary information (entity data, participating employees) and to visualize the information (trips/valid kilometers) of the employees.
- The **Ferrara Play&Go Mobile App** - for the employees, which allows them to track their home-to-work trips and to visualize the achieved results.

A. Web Console

The web console allows each company to configure and manage all information related to the employees participating in the Bike2Work campaign. It is a tool addressed to the appointed MM who is in close contact with the campaign promoter (i.e., the Municipality of Ferrara) before, during and after the execution of the initiative. Each MM can access a dedicated web console with the received credentials. Access can be done via a specific console link. Once logged-into the console, a MM can specify and modify the data useful for the validation of the journeys of the employees. In particular s/he can specify the data related to the company (address, latitude, longitude as depicted in Figure 2(a)), the non-working days and the days when the company is closed (e.g., holidays) as depicted in Figure 2(b).

Once the company information has been defined, the MM can start to insert the data related to the various headquarters involved and to the employees that have expressed the interest to participate to the Bike2Work campaign. It is from this moment that all the employees listed by the MM can start to track their bike journeys and accumulate valid trips and kilometers using the Ferrara Play&Go mobile app (see Section IV-B for details).

As soon as all the needed company information has been inserted in the console, each MM can declare the interest to start the Bike2Work campaign. It is possible to visualize aggregated information about the trips and kilometers made by the different employees, of the different headquarters, etc., eventually also

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8 [http://admin.playngo.it](http://admin.playngo.it)
9 [https://play.google.com/store/apps/details?id=it.smartcommunitylab.playgoferrara](https://play.google.com/store/apps/details?id=it.smartcommunitylab.playgoferrara)
10 [https://apps.apple.com/us/app/id1526145980](https://apps.apple.com/us/app/id1526145980)
choosing the interested period (monthly, global) using a filter component (see Figure 4).

B. Ferrara Play&Go Mobile App

The functionalities supported by the Ferrara Play&Go Mobile App concern the employee’s registration and the management of the employee’s profile, the tracking of sustainable trips, the inspection of employee’s results (e.g., points earned, badges and badge collections, active challenges with completion status, weekly and global leader boards ranking, personal mobility diary), information on weekly and global prizes, as well as the access to game rules and regulation. The application provides a homepage (see Figure 5), in which a summary of the employee’s state is presented. The homepage also presents a set of frequent and immediate actions that the user can perform, e.g., trips tracking.

In the Bike2Work campaign, employees can track trips by bike and can visualize the trips on a real-world map (see Figure 6), both in real-time while they are recording them during their journey, and for past trips stored in their profile.
Each employee who has joined the Bike2Work campaign can directly enter in a dedicated area (see Figure 7) where she/he can monitor her/his progress in the campaign. Access to this private area can take place directly through the Ferrara Play&Go App through a dedicated web link. The main objective of this area is to show to each employee her/his behavior regarding home–to–work mobility. For this reason, it is possible to visualize dedicated information on the Km traveled, the CO2 saved and the number of valid trips. Moreover, each employee can consult the Bike2Work campaign regulations, the privacy information document, and any news dedicated to the campaign in execution.

To validate the bike journeys done to reach the work locations by the employees, the mobile app exploits a dedicated trip validation component. It is a mode detection component that allows comparing a user’s “actual” mode, based on traces of the user’s position and activity sampled during her trip, vs. her “declared” mode, that is, the mode selected by the user when starting the journey tracking through the app (see Figure 5). Only valid trips are sent as player actions to the Gamification Engine and contribute to the progress of the player in the game.

The mode detection algorithm can be configured, depending on the application setting, to also consider some additional information to “certify” the tracked data. For example, in the case of the Bike2Work campaign, the employees are assigned to a specific set of company headquarters that they could reach every working day. The trip validation component checks if each single journey starts or arrives from/to one of the declared locations and if the trip is performed within a company’s working day. If the trip validation component considers the trip valid, the corresponding employee action is sent to the gamification engine component that updates the employee’s state correspondingly. Otherwise, the trip validation component provides a specific motivation for not considering the trip valid (e.g., too fast). The validity outcome, in case of a valid trip, or the explanation of the specific motivation, in case of an invalid trip, is presented to the employee in the mobile app.

V. THE BIKE2WORK OPEN DATA ANALYSIS SUPPORT

Mobility data are everywhere, but not always accessible and understandable. Sometimes cities and local authorities do not know how to get and use them efficiently and how to convey analytics and derived information in a simple way to a non-specialized audience. To reach this goal, we need multidisciplinary approaches that combine information design and data science techniques. A key element is represented by the availability of open data representing transport networks: indeed, open data (i.e., datasets publicly available with open license like OpenStreetMap) are a real treasure that too often remains untapped. Among others, open data about transport networks (road networks, public transport networks, inland water networks, infrastructures for bikers and pedestrians, etc.) represent key datasets, geospatial by nature.

In the case of Bike2Work, the impact of the initiative was analysed implementing an ingestion procedure to get anonymized data from “Ferrara Play&Go” mobile app (i.e., raw GPS points), followed by a map-matching algorithm that reconstructs each trip from the raw GPS logs using the OpenStreetMap (OSM) road network. Generally speaking, a map-matching algorithm is an automatized procedure that combines measures from one or more positioning devices with data from a road network map to provide an enhanced positioning output. This task is usually not straightforward because of the combined effect of measurement errors in positioning data and accuracy errors in road network data. In the context of the Bike2Work campaign in Ferrara, the exploited map-matching procedure handles the positioning uncertainties adopting a Bayesian approach of Maximum Likelihood: the data are projected on the road segments that have the higher probabilities of having generated them. The overall procedure can be divided in different phases. Before the actual map-matching of GPS trajectories takes place, some initialization operations are performed to speed up the following elaborations: road network data for the area are loaded in memory and a road proximity map is created.
This proximity map allows for a fast identification of the road arcs that are close to every given spatial position inside the area. Once the initialization step is completed, the map-matching can start. First of all, the data from each bike trip goes through a trajectory aggregation stage, that serves the purpose of removing useless data and aggregating useful GPS data into trajectories. Then, GPS trajectories are processed in sequence through the two last steps of the procedure: (i) the projection of GPS data into the surrounding road elements and (ii) the identification of the optimal path between the projected data. Another set of automatic procedures calculates different indicators at a single road segment, by timestamp. These procedures are designed to provide practical and easy answers to typical use cases:

- What are the most used routes within the city?
- Do they match infrastructures for bikers?
- What are the critical points for cyclists’ safety?
- Where are cyclists riding the wrong way?

To showcase the results, different map applications have been deployed for sharing data. Web maps have been implemented based on a set of open-source Javascript library (OpenLayers) for displaying spatial data in web browsers, with simple-but-effective interactive maps showing where the streets mostly used by the ‘BIKE2WORKers’ are in Ferrara. Different spatio-temporal indicators have been developed. The map in Figure 8 shows for example where are the streets mostly used by the BIKE2WORK participants in Ferrara, from May 2021 until end of December 2021. In the map, the two major findings are highlighted in blue colour:

- Corso Giovecca, which cuts the city center from east to west and which in the western part is lacking dedicated cycle lanes despite being very popular (see the blue ellipse with label A in Figure 8).
- The new cycle lane, opened in early 2021, that leads from the center to the hospital of Ferrara in Cona village (located to the east) and which appears to be widely used by commuters working at the local health authority and at the University (see the blue ellipse with label B in Figure 8).

In order to make the results of this initiative continuously accessible, an interactive map has also been made available online. The map can be browsed (zoom/pan) and queried. By clicking on a street segment, a user gets information about the number of transits in the selected segment. The number of transits can be filtered for a specific day of the week or other time periods (e.g., weekend, entire week, month, etc.). The selected data can be exploited by the city administrators to identify weaknesses in the network they manage in a secure and timely manner. Additionally, they can be efficiently used to create innovative services, like on-demand services, ride-hailing, etc. so to allow public and private transport companies to increase their performances and enlarge their offerings. In the case of BIKE2WORK, OSM road network is the main source for running algorithms to calculate which are the streets mostly used by the BIKE2WORK participants in Ferrara and what are the critical points for cyclists’ safety.
VI. THE BIKE2WORK EVALUATION

To evaluate the effectiveness of the proposed solution we developed two analyses: the first (see Section VI-A) to accurately analyze the user experience and any behaviour change related to the BIKE2WORK initiative, and the second (see Section VI-B) to demonstrate how exploiting the collected data we can inform and possible guide the involved municipality in improving the urban cyclability.

A. Participants’ Experience and Behaviour Change

To accurately evaluate the user experience and behaviour change related to the BIKE2WORK campaign, we developed a questionnaire, which was sent to all the participants.

1) Questionnaire definition: We developed an ad-hoc questionnaire to collect (1) adequate data regarding the user experience, (2) data on the use of bicycles, and (3) comments and suggestions to improve BIKE2WORK for future campaigns.

The questionnaire presented a core part composed of several items with a 6-points Likert-type scale [33] (from 1 = very negative, to 6 = very positive) aimed at analyzing the user experience. The first part of the questionnaire collected information on the overall experience, users’ habits, satisfaction related to several features of BIKE2WORK (such as tracking, economic incentives, accession procedure, and data visualization), and the intention to participate in future campaigns. Then, the questionnaire provided other ad-hoc items related to the amount of bike use before and during the initiative, and the distance from home to work. This part allows quantifying the extent to which BIKE2WORK had a role in the selection of the means of transport. Finally, the questionnaire offered several open questions for evaluating the strong and weak points of BIKE2WORK, and collecting suggestions and useful data for improving future BIKE2WORK campaigns.

2) Questionnaire results: During the BIKE2WORK campaign, 162 users answered the questionnaire. The 83% of users reported a good overall experience with the initiative (mean = 4.7 ± 1.44), 89% (mean = 5.21 ± 1.2) reported the intention to keep the habits adopted during BIKE2WORK, and the 95% (mean = 5.6 ± .98) reported the intention to participate again in the initiative. The data analysis shows a positive correlation between the overall experience and two BIKE2WORK features: the perception of the tracking ($R^2 = .54$, $p < .001$) and the evaluation of economics incentives ($R^2 = .1843$, $p < .001$). According to some users’ quotes (e.g. ”[I put a low evaluation level for the economics incentives] because not being able to trace the paths, and I did not have any economic incentive”), some issues in the tracking feature led to a decrease in economics incentives, and consequently to a lower overall experience evaluation. We expect that, improving the tracking of routes, we could (1) increase the receipt of incentives, (2) improving their evaluation, and (3) lead to a better perception of the BIKE2WORK initiative.

To analyze whether there was a role of the initiative in the use of bicycles, we first determine the data distribution by performing a Shapiro-Wilk test [34]. It showed that the distribution of the use of bicycles before the initiative departed significantly from normality ($W = .707$, $p < .001$). Based on this outcome, we run a Mann-Whitney-U test [35], finding a statistically significant difference in the use of bicycles before and during the initiative ($W = 16,245$, $p < .001$, $\delta = -.24$), suggesting that the initiative has considerably increased the use of bicycles for commuting from home to work (see Figure 9).

We decided to investigate also the role of the means of transportation on the user experience. Interestingly, the analyses didn’t find differences in the overall experience ($W = 2,661$, $p > .05$), and in the intention to participate again in the initiative ($W = 3,231$, $p > .05$) according to the means of transportation used before the BIKE2WORK campaign. This suggests that the BIKE2WORK campaign was perceived equally positive by both (1) the users who continued to use the bike to move, and (2) the users who changed their means of transportation during the campaign.

In conclusion, the BIKE2WORK campaign significantly increased the use of bicycles, bringing the percentage of participants using the bicycle for home-to-work commuting at least three times a week from 55.8% to 77.9%, with an increase of 40%. The experience has been positive for the users, regardless of the means of transportation used before the initiative. Nevertheless, some elements need to be monitored during the upcoming BIKE2WORK campaigns (i.e., tracking and economic incentives). However, due to a lack of related data, it was not possible to evaluate the overall experience with the distance travelled by users, and the different means of transportation used before the campaign. We expect to investigate these relations in future BIKE2WORK campaigns.

B. Participants’ Behaviour and Streets’ Cyclability

While campaigns like Ferrara BIKE2WORK provide significant nudges and incentives to encourage citizens to use bicycles for home-work commuting, an important aspect that may hinder the regular use of bicycles may be represented by the lack of safe routes to ride. There are already some works discussing ways to optimize the development of bicycle networks. For example, [36] leverages network science algorithms to spot topological limitations of existing bicycle networks to prioritize the development of new bike lanes. In [37], the authors integrated mobility flows to make a more accurate decision based on gaps in the bicycle network and the usage of specific streets. In our work, through the data collected by the Play&Go app, we analyze the BIKE2WORK bicycles
Fig. 10: Users’ trajectories example. (A) A user’s trajectory with low length difference between the original trajectory and the shortest one; (B) a trajectory with large length difference between the original trajectory and the shortest one.

trajectories to understand how much the paths travelled by users diverge from the optimal one (i.e., shortest paths in terms of time and length). With users’ mobility data and street-level information, we aim to understand whether the underwater street network’s safety level plays a role in the paths selected by cyclists. These analyses may provide insights and inform municipalities on how to identify streets that may need interventions to sustain and promote greener means of mobility.

To access street-level information, we download the street network from OpenStreetMap (OSM) keeping only the roads on which bikes are allowed (e.g., we remove highways), and then analyze and process the anonymized GPS traces collected during the Bike2Work campaign. The dataset includes 26,221 trajectories generated by 605 users over six months from May 2021 to September 2021.

Formally, we define a trajectory as follows:

**Definition 1 (Trajectory):** A spatio-temporal point \( p = (t, l) \) is a tuple where \( t \) indicates a timestamp and \( l \) a geographic location. A trajectory \( P_u^n = p_1, p_2, \ldots, p_n \) is a time-ordered sequence of \( n \) spatio-temporal points visited by a user \( u \), who may have several trajectories, \( P_u^{n_1}, \ldots, P_u^{n_k} \), where all the locations in \( P_u^{n_i} \) are visited before locations in \( P_u^{n_{i+1}} \).

In our dataset, \( l \) is a tuple of latitude and longitude with the GPS points sampled every five seconds. The street network downloaded from OSM can be formalized as follows:

**Definition 2 (Street Network):** A street network \( SN = (V, E) \) is a directed graph where the vertices \( v \in V \) are intersections or initial/final points of a road and the edges \( e \in E \) are the streets. Each vertex \( v_i \) has an associated latitude and longitude, while each edge \( e_{(v_i, v_j)} \) has a set of properties \( a_{e_{(v_i, v_j)}} \) (e.g., speed limit, size, etc.) and is connected with two vertices.

To unveil potential issues on the road network, assuming that a study participant tries to reach their workplace/home as fast as possible, we evaluate how much a participant’s observed trajectory deviates with respect to its corresponding shortest paths (both in terms of time and length). For all users’ trajectories, we compute the shortest path between trajectories’ origins (\( p_1 \in P \)) and destinations (\( p_n \in P \)). First, we map the origins and the destinations with the nearest \( v_i \in SN \) using the ball tree algorithm for Haversine nearest neighbour search implemented in osmnx. Then, we apply the Dijkstra algorithm to compute the shortest path on \( SN \). We generate two different shortest paths that we use to create two weighting schemes for the edges: (i) the time needed to commute on an edge, and (ii) the length (in meters) of the edge. The lower the time or the length, the more similar the observed trajectory is to the shortest one (see Figure 10).

A reason for cyclists to deviate from the optimal path may not just be related to the distance to commute. The street network may play an important role. Suppose that a cyclist has to commute between two destinations nearby, but the shortest path is a dangerous road. It is likely that a cyclist will use a longer but safer path. To validate this hypothesis, we computed the so-called Level of Traffic Stress (LTS) [27], an index that, given some meta-information about the street (e.g., speed limit, street size, type of cycle lane), classifies the streets into four different levels of danger for cyclists. LTS 1 represents streets with no or little stress, suitable for children.

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16 https://osmnx.readthedocs.io
We indicate the LTS of a specific edge as $e^{LTS}$. Among the other attributes, have an associated LTS. The average score for a trajectory is computed as follows:

$$\text{score}(T) = \frac{\sum_{e \in T} e^{LTS}}{|T|}$$

The score for a trajectory is the average LTS score of all the street segments used to travel from the origin to the destination.

Comparing the observed original trajectories with the corresponding optimal trajectories (i.e., shortest paths), we observed that cyclists in Ferrara not only tend to travel longer paths (original trajectories (median) = 3451.82 meters; optimal trajectories (median) = 2948.81 meters), but also travel on streets that display lower stress levels. As shown in Figure 11, the grey dotted line represents the scenario in which the LTS of the optimal and observed trajectories would be the same (slope = 1, intercept = 0), but travelling on the shortest route would have been more stressful (slope = 0.3437, intercept = 1.3851). This may suggest that cyclists in Ferrara avoid streets that are less bike friendly. Similar results were obtained using shortest paths based on time.

These analysis could be potentially used to find the trajectories that show a large divergence in the average score between optimal and observed trajectories. Therefore, based not only on the stress level but also on how much a street is used by cyclists, we could locate the streets that are more problematic. This in turn could be used to inform municipalities and possibly guide them in improving the cycling road network.

VII. CONCLUSIONS AND FUTURE WORK

Among the major impacts the Bike2Work initiative includes the analysis of open-source large data sets which supports policy and decision makers, urban planners and designers. As we have seen in this paper, the end-to-end software solution presented not only supports the Mobility Managers and the employees throughout the sustainable mobility campaign but has been conceived to understand the progress and the impact of the running initiative. After the first Bike2Work campaign’s execution, some initial results have been obtained and reported. We will continue running the campaign for the next year (till October 2023). Taking advantage of the experience gained and reported here, the next steps will be to improve both the methods and supporting technologies to revitalize the campaigns introducing new motivational methods (i.e., personalized gamification challenges to introduce competition among employees) for the last period of the project.

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