Bicycle network needs, solutions, and data collection systems

A theoretical framework and case studies

Reggiani, G.; Salomons, A.M.; Sterk, Merel; O'Hern, Steve ; Daamen, W.; Yuan, Y.; Hoogendoorn, S.P.

DOI
10.1016/j.cstp.2022.03.006

Publication date
2022

Document Version
Final published version

Published in
Case Studies on Transport Policy

Citation (APA)
Reggiani, G., Salomons, A. M., Sterk, M., O'Hern, S., Daamen, W., Yuan, Y., & Hoogendoorn, S. P. (2022). Bicycle network needs, solutions, and data collection systems: A theoretical framework and case studies. *Case Studies on Transport Policy*, *10*(2), 927-939. https://doi.org/10.1016/j.cstp.2022.03.006

Case Studies on Transport Policy 10 (2022) 927–939

Contents lists available at ScienceDirect

Case Studies on Transport Policy

journal homepage: www.elsevier.com/locate/cstp

Bicycle network needs, solutions, and data collection systems: A theoretical framework and case studies

Giulia Reggiani [a,*], A. Maria Salomons [a], Merel Sterk [a], Yufei Yuan [a], Steve O'Hern [b], Winnie Daamen [a], Serge Hoogendoorn [a]

[a] Transport & Planning Department, Faculty of Civil Engineering and Geosciences (CiTG), Stevinweg 1, 2628 CN Delft, The Netherlands
[b] Transport Research Centre Verne, Tampere University, P.O. Box 600, FI-33014 Tampere University, Finland

ARTICLE INFO

Keywords:
Bicycle data collection system
Bicycle network needs
Nation-wide survey

ABSTRACT

Similarly to Maslow's pyramid of human needs, we theorize that cities have a pyramid of bicycle network needs that depends on their level of bicycle culture. As an increasing number of data sources emerge for bicycle data collection, transport authorities face the challenge of understanding how to use the data and which data sources are fit for their network needs. This article defines a framework that relates the bicycle network needs of cities with data collection systems. We showcase the need-driven framework through a case study of Melbourne, Australia, a bicycle ignorant city, and surveying 15 municipalities (and their consultancies) of the Netherlands. By using the proposed need-driven framework cities can understand how to fully exploit bicycle data collection systems and make a systematic plan.

1. Introduction

As an increasing number of data sources emerge for bicycle data (Lee and Sener, 2020), transport authorities face the challenge of understanding how to use the data and which data sources can be fit for their network needs. Some recent studies discuss how bicycle data is produced, shared and analysed in smart cities (Behrendt, 2016; Nikolaeva et al., 2019). However, the availability of data collection technologies does not automatically translate into collected data sets and use in practice. For example, research has shown that while many cities consider safety of major importance for bicycle interventions many do not collect data to assess risk (Grossman et al., 2019). This opens the discussion about which type of bicycle data a city should collect given its policy objective.

Despite the accumulation of literature pointing at the importance of bicycle data, so far, no study has proposed a framework to determine what type of data cities should collect, conditional on their level of bicycle culture (LoBC) and network needs. Cities have different LoBC (as described in Section 2): some have never focused on stimulating cycling whereas others were so successful in doing so that are now struggling to deal with rush hour flows. For this reason, we argue that each city has different *bicycle network needs* (BNNs) - the set of requirements that a street network should meet in order to improve its bicycle operating functions given their LoBC. To understand which functions a bicycle network should meet, we refer to the basic principles of safety, directness, coherence, attractiveness, and comfort defined by the traffic and transport knowledge platform CROW (CROW, 2017). Examples of BNNs are the initial development of a network, expansion of the network, maintenance of the network, capacity management, parking facilities at destinations, and ITS (intelligent transport systems). To fulfil their BNNs cities require different policies; some cities need to first focus on bicycle safety to encourage cycling as a means of transport, whereas others need to collect real-time data on bicycle flows for advanced route guidance systems that mitigate congestion. Developing cycling plans requires data, however, too often there is a lack of knowledge on which type of data is available and is needed to meet the city's BNNs.

In this paper, we tackle the relation between BNNs and data collection systems by developing a framework - denominated the "journey to bicycle data collection"- which relates the BNNs of cities to data collection systems. Fig. 1 reports a visualization of the proposed framework that can be described in a need-driven fashion as five sequential steps that city experts can carry out:

1. identify the main BNNs of a city

---

* Corresponding author.
E-mail addresses: G.Reggiani@tudelft.nl (G. Reggiani), A.M.Salomons@tudelft.nl (A.M. Salomons), merelsterk@hotmail.com (M. Sterk), Y.Yuan@tudelft.nl (Y. Yuan), steve.ohern@tuni.fi (S. O'Hern), S.P.Hoogendoorn@tudelft.nl (S. Hoogendoorn).

https://doi.org/10.1016/j.cstp.2022.03.006
Received 8 October 2021; Received in revised form 23 February 2022; Accepted 11 March 2022
Available online 16 March 2022
2213-624X/

2. define solutions that fulfil those BNNs
3. understand the information needed as inputs for the solution
4. define the data requirements to derive the required information
5. establish which data collection systems satisfy the data requirements.

Although we believe that a need-driven approach is the most effective way to design and deploy a bicycle data collection system, it is often the case that municipalities go through the framework in a “technology push” approach (reversed order). Starting from the technology (to be) deployed they look for applications of the data and the BNNs that can be fulfilled. The limitation of a technology push approach is that the technology deployed may never fulfil the BNNs, which implies inefficient use of resources. Also, a combination of the two approaches is possible, thus once sensors are installed, municipalities search for further options to use the data.

This article aims to summarise the BNNs, solutions, and data collection systems of urban bicycle networks to support practitioners to identify the sensors or data collection systems that best match their BNNs. In doing so we delineate a framework that shows international best practices and relates them to BNNs and level of bicycle culture (LoBC). Such a framework guides how and when practitioners should implement data collection systems for bicycles. The Netherlands, with its mature bicycle culture, was chosen as a study area to understand the framework. Empirical evidence, from a survey with 15 municipalities, illustrates the framework logic; the Dutch cities have bicycle sensors that meet the BNNs of bicycle-friendly places. The result of the survey is an unprecedented inventory of the deployed sensors, extracted information and ICT (information and communication technology) solutions used for bicycle detection and data collection at a major intersection in the Netherlands. As a consequence the survey sheds light on the potential availability of bicycle data that there is in the Netherlands and inspires more research on possibilities of how to apply it, thus linking data availability with BNNs. Second, using the developed framework a case study in Melbourne, Australia, was undertaken to assess the alignment of the framework with a bicycle ignorant/emerging city.

The paper is structured into two main parts: a theoretical framework and empirical case studies. The theoretical section follows the structure of the framework presented in Fig. 1. Section 2 identifies BNNs of cities, Section 3 presents macro-classes of possible solutions, and Section 4–6 describe respectively the input information, data requirements and data collection systems (or sensors) needed for the functioning of each solution. The article follows in Section 7 and 8 with empirical evidence, collected via a survey, on bicycle data collection systems of bike networks in the Netherlands and a case study in Melbourne, Australia. After discussing the outcome of the survey and case study in Section 9, conclusions are drawn in Section 10.

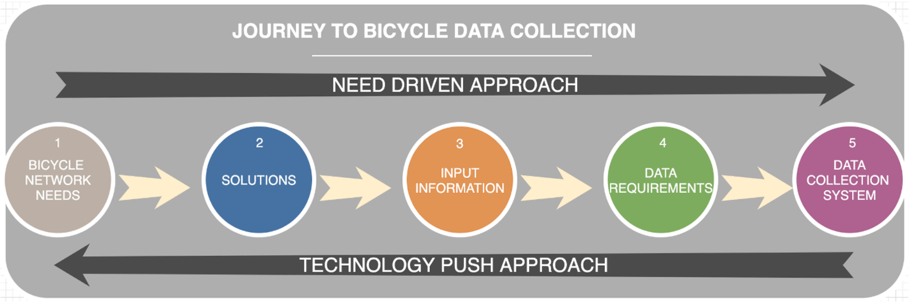


Fig. 1. Journey to bicycle data collection – conceptual framework.

2. Bicycle network needs (BNNs)

While some studies have attempted to rank cities’ bicycle friendliness, to the best of our knowledge, no study has yet identified classes of cities based on similarities in their needs. Grouping cities based on their BNNs can help in identifying solutions. We propose a classification of cities inspired by Maslow’s pyramid of needs (Maslow, 1943). The *hierarchy of needs* theory argues that humans have a pyramid of needs in which lower layers of the pyramid represent the basic physiological (e.g. food, water, sleep, etc.) and safety needs, that must be met before focusing on other (secondary) needs like social, self-esteem, and self-actualization. Needs lower in the hierarchy must be satisfied before individuals can focus on higher needs.

Similarly to Maslow’s needs, we hypothesize that cities have a pyramid of needs. With respect to cycling, we argue that cities have different BNNs depending on their *Level of Bicycle Culture* (LoBC) (which defines the levels of the pyramid). As mentioned by Pelzer (2010) bicycle culture consists of the social environment as well as material and physical circumstances. Based on the bicycle culture, a city has specific BNNs (needs relating to the physical environment). The bicycle culture of a city can be established by comparison of bike traffic volumes (Oosterhuis, 2013). In addition to this, the criteria we use to characterize the LoBC are bike modal split, bike traffic volumes (referring to crowdedness), safety, and comfort. An indicative characterization of the levels is reported in Fig. 2. We define five LoBC: ‘bike-hostile’, ‘bike-ignorant’, ‘bike-emerging’, ‘bike friendly’, and ‘bike-dominant’ to identify the main classes of BNNs, as shown in Fig. 3. Bike-emerging cities should strive to become bike-friendly, however, bike-friendly cities may need to avoid becoming bike-dominant if local volumes of cyclists exceed network capacity. During the development of our framework, a study about levels of bicycle maturity was published (McLeod et al., 2020), showing the relevance of the topic. While the research by McLeod et al. (2020) does not focus on BNNs nor data

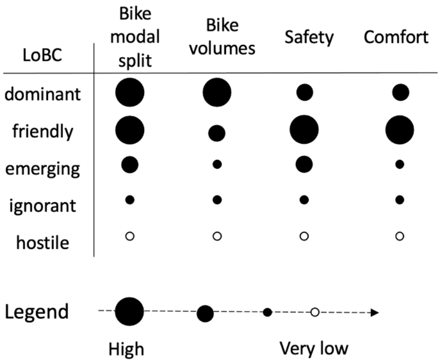


Fig. 2. Levels of bike culture and the criteria that hold for the corresponding level.

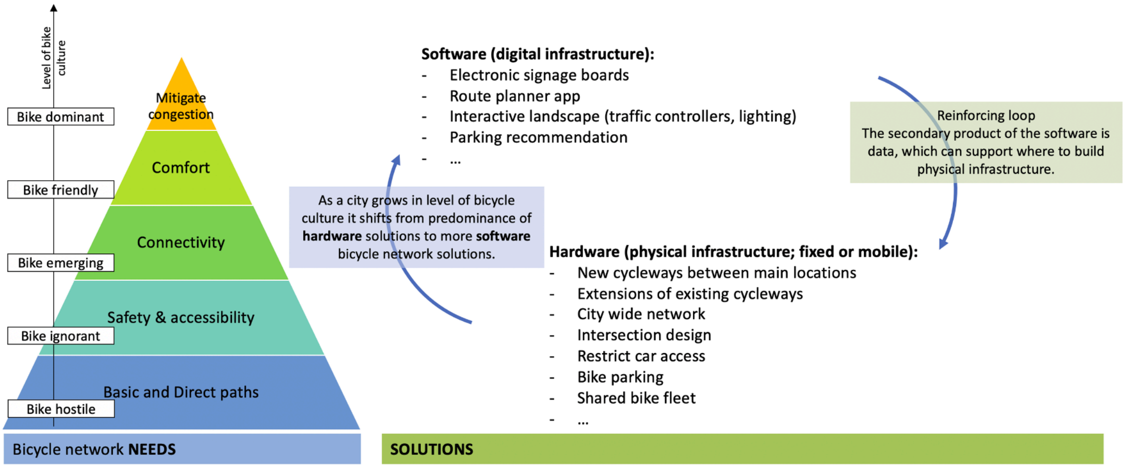


Fig. 3. Pyramid of bicycle network needs associated to the Level of Bicycle Culture (LoBC) and the related classes of network solutions.

collection systems for bicycles, it does classify best practices related to policy consistency, advocacy, integration with public transport and planning tools into levels of bicycle maturity[1].

The levels of bicycle culture defined by us are:

- **Bike-hostile:** is a city that is mainly focused on car infrastructure development. This type of city needs a starting point made of **basic bicycle infrastructure streets**. Its street network requires **convenient (direct and well-known) bike connections** between important areas of the city. At this stage, it is more important for a city to redistribute road space among modes with fast-to-build and inexpensive bike lanes rather than constructing more expensive segregated bike tracks. This basic infrastructure will enable some people to cycle. Bike modal split, volumes, safety and comfort are absent or very low in this type of city.
- **Bike-ignorant:** is a city that starts having an interest but has never made plans to develop cycling as a mode of transport. This type of city does not have a connected bike network, just a few sparse links that are not part of a coherent plan. It may (or may not) have a few separated bike paths. If such a city has an interest in starting a bike culture it should first-and-foremost look at **safety** (Winters et al., 2011) and **accessibility** of its streets. By accessibility, we mean the ability to access important destinations by travelling along the bike network. Thus, it relates to the user's access to the network, and also to the connection of the network to important areas of the city. It can do so by extending the existing bike streets and converting the bike lanes along the major vehicular roads into segregated bike tracks to create safe access to main destinations in the city. Cycling conditions are poor resulting in low bike modal split, volumes, safety and comfort (Silva et al., August 2018).
- **Bike-emerging:** is a city which has started to plan for cycling mobility but does not have a well connected bikeable network yet. This type of city is interested in understanding latent cycling demand (Lovelace et al., 2017), cyclists' use of the network in order to identify weak points of the infrastructure (Rupi et al., 2019) to improve the **networks overall connectivity**. The requirement is to increase connectivity of the network beyond the main destinations. Bicycle modal split is at a medium level as well as safety, whereas comfort and bicycle volumes are low.
- **Bike friendly:** is a city that has successfully attracted people to cycle and has a well-connected bicycle network. Bicycle modal split, safety and comfort are higher than bike-emerging cities. This type of city may want to increase mode share even more, by making multi-modal trips easier. The aim is to make the existing bike network even more **efficient** and **comfortable** to cycle on, by focusing on travel times, comfort, and integration with public transport (Pucher and Buehler, 2007; Buehler and Dill, 2016; Centre for Public Impact, 2016).
- **Bike-dominant:** is a city where cyclists rule the streets. These places are so successful in attracting cyclists that they start to experience unforeseen problems in the bicycle world. The few cities that have reached this stage, like Amsterdam and other Dutch cities, are proof of a new type of urban cycling problem (City of Delft, 2019; De Groot-Mesken et al., 2015). The bicycle volumes and density levels, at some points of the network, are beyond the capacity of the bike paths resulting in a reduction in perceived safety and comfort. Cycle lanes are already in place, but more is needed to improve cycle flow, especially during rush hours. This situation relates to the vehicular world, where congestion and capacity problems have been an issue much earlier. New solutions are needed to **mitigate congestion** in the bicycle domain.

Our framework does not have the ambition to classify cities bases on their performance; it rather identifies clusters of BNNs and guides cities to find solutions and data collection methods that fulfil these BNNs. Note that each level of the pyramid presents the main BNN, meaning that a city may (and in fact should) also focus on other minor BNNs at the same time. For example, if one focuses exclusively on safety, a city may end up with a very safe cycle path between areas for which there is no demand. People will be stimulated in using the bike network only if they can go from their home to where they want to, by bike, that is to say, they also require higher-order needs of a well-connected network.

As a final remark, let us note that next to network-wide identification of needs, also more local identification of network pinch-points is possible. To breakdown the network-wide needs into link-level (i.e. road) needs a priority map is used; this map shows which links have the largest impact on the performance of a city network. To this end, a couple of intermediate steps should be taken, as illustrated in Hiddink et al. (2017).

The local network needs can be identified via link specific set of functions and priority criteria (which lead to function maps and priority maps of a city). Three network link functions are defined:

1. Fast bicycle path: bundling connection of (commuter) traffic from external areas to specific prime locations, where a low travel time (or high speed) is decisive,
2. Main bicycle path: bundling connection between all prime locations, where facilitation of large traffic flows is decisive,

---

[1] For an equivalence between our LoBC and the maturity stage identified by McLeod et al. (2020), 'bike friendly' level matches both 'tactic' and 'practice' maturity stage.

3. Bicycle paths: cycle paths where access to residential areas is the main feature.

The priorities are determined based on three criteria:

1. The number of preferred[2] routes on a link,
2. The importance of the routes on a link (depending on trip purpose),
3. The magnitude of traffic flow on a link.

Per link, these three criteria are counted and combined to a priority ranging from one to six. The magnitude of actual traffic flows can be estimated or substantiated by data or models. For cyclists, public transport (with respect to the number of travellers) and pedestrians this is not always trivial due to lack of data and adequate models. Finally, policymakers may use a combination of priority maps and function maps to show where essential connections are located and prioritize network improvements. We refer to Hiddink et al. (2017) for details and implications for monitoring.

3. Solutions for BNNs

This is the second step of the framework, which focuses on solutions that can help in reaching BNNs. We identify two macro-classes of solutions: *hardware* and *software* solutions (see Fig. 3). With *hardware* solutions we indicate physical infrastructure interventions such as construction or redesign of cycleways, whereas with *software* solutions we indicate digital infrastructure solutions such as mobile phone applications for route planning applications and demand-responsive traffic signal controllers. As a city grows in level of bicycle culture it shifts from predominantly *hardware* solutions to more *software* solutions, although the hardware still needs to be in place and maintained. As an example, a non-physically connected bicycle network will not achieve connectivity only by means of ICT solutions (route guidance apps can suggest more connected routes than the shortest route that one has in mind, but they will only tackle the BNNs to a small extent). On the other hand, software solutions like interactive landscapes do provide a solution to the need for more comfort in networks that have fulfilled the primary BNNs of basic and direct paths, safety-accessibility and connectivity.

In general, the distinction between hardware and software solutions is not so clear-cut, since most software solutions may require also hardware. Thus, our classification of the solutions in the following sections should not be seen as a rigid truth but as a hint to understand the distinctions.

This section provides a first attempt to inventory bicycle network solutions, found in the literature, based on the BNNs. The focus is on the infrastructure network solutions (expansion or improvement of bicycle streets). Other solutions from the land-use domain (such as urban density and mixed land-use to increase the number of different amenities found around each location) can also improve bikeability but are beyond the scope of this article. The following is by no means an exhaustive list of solutions but it is indicative of the range of options. Each sub-section introduces solutions from a level of the pyramid of needs (from bottom to top).

3.1. Solutions for basic and direct needs

Solutions at this stage of BNNs are mainly focused on identifying where new basic infrastructure should be located and building it. This will attract some people to cycle within the city. The main solution types are:

- **Build bike lanes and bike paths between main locations**: in order to cycle the prerequisite is to have some well-marked streets for cyclists, possibly segregated from vehicles (*hardware* solution). The debate on where to start building bicycle infrastructure has developed the concept of potential for cycling, i.e. where cities have higher or lower potential demand so to encourage cycling (Silva et al., August 2018). Good connections to universities and schools are known to attract students considered as forerunners for cycling in cities (Pogačar et al., 2020). Cycling potential demand is the required information (discussed in Section 4) for the implementation of this and other solutions.
- **Bike sharing fleet**: provides access to bicycles with a pay per use system. This *hardware* solution enables people without a personal bike to cycle in a city and thus to use the infrastructure (Song et al., 2020). In addition, bike-sharing systems make large amounts of data available that can guide decisions on where to extend the bicycle network (Lee and Sener, 2020). Whether the data is owned by the municipality itself or by private bike-sharing companies makes the difference in how the information can be exploited.

3.2. Solutions for safety and accessibility needs

Increasing safety can be achieved by reducing the chance of a crash or the impact of the crash. The main interventions to improve safety and accessibility are:

- **Infrastructure re-design or car restrictions:** *hardware* solutions that reduce the chance of a crash while cycling are road, intersection, or public space redesign that allocate space for cyclists. Other solutions for residential areas and shared spaces are to limit the speed of cars or restrict their access.
- **Traffic signal:** A separate traffic signal for cyclists is a *software* solution that increases safety (as well as comfort) because cyclists have their own signal phase which reduces the conflicts between cars and cyclists or makes conflicts less severe.
- **Lighting:** Intelligent bicycle lights that increase visibility at night when a cyclist is approaching are another *software* solution to increase perceived safety.
- **Extension of existing links:** this *hardware* intervention aims at increasing accessibility to the existing bicycle network. Ultimately, more residents of a city will have access to more locations by bicycle.
- **Safe journey planner:** a *software* tool to plan a safe and comfortable route, avoiding roads perceived as dangerous for cyclists such as busy roads without appropriate bike infrastructure, tram tracks or cobblestones (an example is the route planner app of Ghent (BE)[3]).
- **Cooperative systems**: these are *software* solutions to allow communication between cyclists to vehicle (B2V)[4] or between a cyclist and roadside infrastructure (B2I) (Nikolaeva et al., 2019). This would reduce the risk of a crash by having the road users share location information among themselves and also gather data on crashes, and close collisions that can be used to redesign infrastructure.

3.3. Solutions for network connectivity needs

On one side cities should seek for overall connectivity of a network (i.e. all locations connected to all others), on the other they should not build superfluous infrastructure, between areas with little or no latent demand. The main solution types for connectivity needs are:

---

[2] Preferred routes are based on policy and route choice criteria. An example of policy statements could be ”no main cycle routes through the city centre”.

[3] https://fietsrouteplanner.stad.gent/index.html?language = en_US

[4] various projects are ongoingly related to collaborative bicycle to vehicle (B2V) safety. Tome is an example of this: https://www.tomesoftware.com/b2v/#About

- **Increase network-connected components:** this *hardware* solution aims at connecting the incomplete and separate bicycle network. There is ongoing research on which network growth strategies to follow (Orozco et al., 2020); connecting the closest connected components, connecting the largest connected components, connecting areas with the highest demand, and connecting areas with wider streets are all possible solutions that urban planners chose depending on the city context.
- **City-wide network matching the latent bicycle demand:** Planning the network as a whole is another valid *hardware* solution, rather than as independent and disconnected projects. A systematic review of infrastructural interventions to promote cycling is presented in Mölenberg et al. (2019), where the city of London is presented as an example of city-wide network extension.

3.4. *Solutions for comfort needs*

In order to achieve increased levels of comfort along a bicycle network, here are some solutions found in the literature as well as some common practices implemented by Dutch and Danish municipalities:

- **Route guidance app:** are a *software* solution that recommends comfortable bicycle routes to users. Many cities start to offer such applications that recommend routes based on distance and some other criteria that attempt to measure bicycle-friendliness or comfort. For example, one can select the quietest, fastest or a balanced route when cycling in the UK thanks to its journey planner[5]. How to measure the comfort of a bicycle route is an ongoing challenge. In Section 4 we discuss the information needed for this type of solution. Let us note that, while it is acknowledged that cyclists choose their route differently to drivers of vehicles, also considering contrasting objectives (Ehrgott et al., 2012) it is not trivial to identify which is the most comfortable route when considering more than one objective.
- **Vehicle-actuated traffic control:** this is a *software* solution that activates traffic controllers based on bicycle and vehicular demand (Muller and De Leeuw, 2006). This is a well-established solution in many Dutch cities (as results show from our survey in Section 7). A further improvement of this application could measure the bicycle and vehicular demand based on the number of people waiting by bike versus by car and prioritize the direction with the highest amount of people queuing.
- **Dynamic green wave adaptation:** green waves are common practice in some bike-friendly cities. The aim of this *software* solution is to synchronise consecutive traffic lights so cyclists do not need to stop at intersections, which increases comfort and decreases waiting times. Dynamic green waves can adapt the green wave to the cyclists' current travel speed (De Angelis et al., November 2018).
- **Connection to Public Transport**: public transport agencies play a major role in facilitating cycling (McLeod et al., 2020). Efforts should start with a *hardware* type of solution of secure bicycle parking at major train stations and aim at integrating bicycle and public transport consistently across the network also with *software* type of solutions.

3.5. *Solutions for congestion needs*

As cities become bike-dominant, new solutions are needed to tackle the new (sometimes unforeseen) problems however there are not many implemented examples of these types of solutions. Bike-dominant cities are facing problems such as congestion and bike parking shortages that require new solutions for the bicycle mobility world. Hereafter we provide exploratory solutions tested in some bicycle dominant cities and ongoing research ideas. Since the bike-dominant type of BNNs are fairly recent and not spread worldwide, the solutions implemented are limited.

- **Intersection re-design:** intersections are points where flows from different directions meet and partition over the network. Both *hardware* and *software* solutions can be implemented. The city of Amsterdam, has developed a cone-shaped crossing for cyclists, which aims to avoid queue spillback effects by shortening and widening the shape of the queued cyclists[6]. Delay at intersections can also be reduced by guiding cyclists to queue closer together, as shown in the empirical study by Wierbos et al. (2021). A *software* solution is to allow longer green phases at the traffic controller to discharge queued cyclists.
- **Parking advisory:** are digital signs used to guide cyclists to free parking spaces. This can help cyclists when parking is crowded to find a spot and keep the parking lot tidy. Some solutions guide cyclists (through digital signs on the street and applications) in finding a parking space for their bike [7].
- **Route guidance based on real-time bicycle level of service (BLoS):** for cities experiencing congestion problems route guidance apps should recommend non-congested routes, in contrast to guidance apps for emerging cities that focus on safe and comfortable routes (sometimes also the most popular among cyclists). To have a realistic picture of the quality level of a bicycle street BLoS is used. BLoS in bike-dominant cities should incorporate variables that describe the (real-time) bicycle traffic conditions based on factors such as flow, travel time and speeds (Kazemzadeh et al., 2020).

4. Input information

Once a city identifies the solutions to fulfil its BNNs, the next step is to understand all types of information required before, during, and after implementing a specific solution. Information can be related to the current situation or a future scenario depending on the planning stage. In general, first observations of the current situation are used to assess the state of the bicycle infrastructure and network operation characteristics. Secondly, future demand or bike crashes can be predicted to decide on a network expansion (or change). The solutions we describe in the following subsection can be seen as observed information; however, it is also possible to predict many of these types of input information. In later stages, during the data requirement and data collection, some information may be discarded due to difficulty in measuring it with the currently available technology.

This section is divided into five subsections, containing the main information required as input for each level of bike network solution (from bottom to top in the pyramid of needs).

4.1. *Information for basic and direct paths*

A first step is to map the current routes cyclists can take. The following step identifies current and potential cycling trips. Based on the results of the two previous phases planners can identify important origins and destinations and use the map to see where links are missing. Hereafter we report the input information to execute this type of solution:

- **Origin – destination (OD) of trips**: this information enables the identification of cycling desire lines and the neighbourhoods of a city which have high potential to start cycling (Lovelace et al., 2017).

---

[5] https://www.cyclinguk.org/journey-planner

[6] https://bicycledutch.wordpress.com/2018/04/10/intersection-upgrade-a-banana-and-a-chips-cone/

[7] https://www.europeandataportal.eu/en/news/discover-p-route-dutch-bike-parking-application

This provides geographical information for the city from which planners can infer which locations need a convenient bicycle connection.

- **Cycling potential demand:** potential demand identifies where future bicycle trips may occur in a city, which may, or not, be observable yet. Cycling potential tools exist to extract bicycle desire lines (potential demand) information. Cycling potential tools use OD information or mobility data to explore the geographical distribution of cycling potential, at point, area, origin–destination, route or individual levels (the reader may refer to Lovelace et al. (2017), Olmos et al. (2020) and Silva et al. (August 2018), and reference therein).
- **Age and gender**: this demographic information can provide useful statistics on who are the potential cyclists of specific areas. By knowing such information a municipality can define long term strategic solutions to attract cyclists of specific user groups.

4.2. *Information for safety and accessibility*

Safety is measured by the chance of a crash (bike exposure) in combination with the impact of the crash. Accessibility is measured by the number of amenities that are reachable by bike. Hereafter we report the input information needed to improve safety and accessibility:

- **Bike-car collisions**: this information is needed in order to redesign and improve the safety of bicycle infrastructure. Bike-car collision records are usually a highly incomplete source of data due to the under-reporting of bicycle collisions especially when collisions are minor (Watson et al., 2015). Thus, this data points out major crash locations which may not always be the locations where cyclists feel most unsafe.
- **Bike-car conflicts**: conflicts are events that would result in a collision unless one of the involved parties changes behaviour (i.e. near misses). Using traffic conflicts as a proxy for safety diagnosis is becoming more popular since they are more frequent than collisions and they identify the preconditions that lead to collisions. Computer vision can detect such collisions as shown in Sayed et al. (2013).
- **Bike only crashes**: or bicycle-bicycle crashes happen especially when there are large speed differences. Crashes can happen also with cyclists alone, when cyclists fall, because of poles or curbs, or uneven cycle paths. This information is crucial for infrastructure redesign.
- **Exposure data – volumes**: Bicycle (and vehicle) counts are necessary to measure exposure levels in order to assess risk. New cycleways can alter risk exposure by encouraging or discouraging travel via bicycle. Measuring exposure levels is fundamental especially in before-after studies. However, still many bicycle emerging cities do not collect bicycle counts, despite stating the importance of safety in bicycle planning (Grossman et al., 2019).
- **Residential, employment and activity locations**: geographical information on resident's household location, employment locations, and main activities in a city is needed to measure accessibility, and plan how to improve it. Besides accessibility to the network, information on residents' accessibility to a bicycle is important (Song et al., 2020).

4.3. *Information for connectivity*

The necessary information for network connectivity improvements are:

- **Trips**: more detailed demand data is needed, than just origin–destination to consider connectivity of all relevant destinations in a city. Knowing the trips of cyclists allows for the mapping of their movements over a network allowing for an understanding of route preferences. This information is essential in network growth decisions.
- **Physical network data**: is important to have an updated visualization of the bicycle network so to identify network growth strategies. Strategies can aim to increase the connectivity of subcomponents or the whole network.
- **Placement of new bike links**: this information is fundamental for extending connections of a bicycle network. It can be extrapolated based on diverse bike growth strategies available (Orozco et al., 2020) in combination with bicycle potential demand.

4.4. *Information for comfort*

To implement solutions for bicycle network comfort this information is worth collecting:

- **State of the infrastructure:** information on the infrastructure conditions (e.g. potholes) enables timely maintenance and repair of the infrastructure.
- **Position of cyclist**: having this information enables a wide variety of solutions. For example, knowing the position of an anonymous user approaching the intersection allows for the implementation of bicycle responsive traffic controllers.
- **Speed of cyclist**: in order to have more sophisticated traffic controllers, extra information about the speed of the approaching cyclists could be measured. The advantage for a cyclist would be to keep their current speed without the need to decelerate. For example, in Dabiri et al. (2019) a speed advice system for cyclists is modelled so that the traffic controller learns the reaction behaviour of cyclists and adapts its future advice.
- **Queue of cyclists**: this information would be an improvement to dynamic traffic controllers willing to minimise the waiting time of the overall system. By incorporating the queue information they could weigh the incoming flows based on the number of users in the queue.
- **Bike density**: this information is extremely relevant for bike-dominant contexts. The Covid-19 pandemic urged for physical distancing, also while cycling and additional measures at intersections (Salomons, 2020). Thus density information has become extremely relevant during the Covid-19 pandemic as a measure of safety and comfort of users.
- **Emotions** this information can provide insight regarding the mood characteristics of cyclists at different places. To the author's knowledge, this information is currently not being collected by any municipality. However, by knowing such information a municipality can have an even more detailed level of service measure. By looking at low emotions planers may define and know when to trigger custom strategies to re-route, in space and time, bicycle flows so to ultimately mitigate congestion.

4.5. *Information for congestion-free lanes*

Some bicycle information that could be useful for congestion-free solutions are:

- **Queue of cyclists**: this information is useful to understand when there are spillover effects, and dynamically allocate longer green light phases to mitigate them.
- **Parking occupancy**: occupancy information of big parking lots is useful to guide users quickly to a free spot. This way a city makes better use of existing parking by distributing users where there is more available capacity.
- **Flow**: this information is useful for users to plan their routes. Real-time flow information is needed to develop apps that function similarly to Google Maps, Waze and other vehicular route guidance apps.
- **Bicycle level of service (BLoS)**: is a measure of on-road bicyclist comfort level as a function of a roadway's geometry and traffic

conditions. This measure is used in bike-emerging cities to assess bicycle path conditions based on static street parameters (such as number of lanes per direction and path width) and the neighbouring vehicular traffic flow characteristics. However, for bike-dominant cities, BLoS can also incorporate information that describes the (real-time) bicycle traffic conditions based on factors such as flow, travel time and densities (Kazemzadeh et al., 2020).

5. Data requirements

This step of the framework translates the input information, needed for the solution, into specific data requirements. This phase determines the quality of the solution application. In general, the higher the quality of the data (in terms of accuracy, reliability, latency), the more costly the data collection will be, but also the higher the performance of the application. However, some applications may require lower quality data than others to perform adequately. For example, one may need travel times as input information. Depending on the data requirements travel time can be estimated daily, hourly, or per minute. If a city wants to reroute cyclists depending on current travel times on the network, having only daily data is not useful. In that case, per minute travel time information may be needed to have a realistic (close to real-time) description of road conditions. Another application is speed advice near intersections (Dabiri et al., 2019). Such a system requires detailed information on queue lengths at intersections and position information of the cyclists (as well as connectivity to inform the cyclist). Limited accuracy or too large latency would incapacitate the efficient functioning of the application.

This section describes the main data requirements to consider to translate the input information (step 3 in Fig. 1)) into a data collection system (step 5 in Fig. 1). These data requirements can apply to different input information from the previous step. The choice of the data collection system (step 6) is bound to the data requirements identified in this step. We point out how the choice of the data collection system is not defined by the input information required but by the information combined with the data requirements (frequency, accuracy etc.).

- **Microscopic or macroscopic data**: depending on the information needed the data requirements will be per individual or aggregated.
- **Frequency of the measurements**: the closer to real-time the information needed the more frequent the measurement intervals
- **Data quality**: refers to the accuracy of the data (e.g. expressed as the relative error in the position, speed, etc.), the reliability of the data (the % of sufficiently accurate measurements), and the latency of deployment (how long does it take for the data to become available[8])
- **Representative of user population**: the more the information needs to be representative of the cycling population, the more the data needs to be collected from the total amount of cyclists and not just by a sample. Fixed location sensors have the potential to detect all users in contrast to mobile phone apps or GPS systems which will realistically be downloaded only by part of the population. There is evidence that cyclists who use smartphone apps to record their bike rides have different riding and socio-demographic attributes compared to those who do not (Garber et al., 2019).
- **Privacy sensitivity**: when deciding to collect personal data, authorities involved need to consider the amount of privacy-sensitive data they can – and want to – collect. In some countries, organizations are compelled to protect these data and to have control over the protection. Meaning that one may decide to not store personal data, or process it (or aggregate it) in ways that make it less privacy-sensitive. If on one side cycling should not be excluded from the ”smart” and digital innovation context of cities (Behrendt, 2016), we should not collect privacy-sensitive data without a real need.

6. Sensors and data collection systems

This last step of the framework translates the data requirements into sensors or data collection systems. Based on data requirements (step 4 in Fig. 1) and the input information (step 3 in Fig. 1) planners decide the data collection system. At this stage also the techniques for state estimation are decided so to extract the required information.

Table 1 provides an overview of the sensor technologies and methods in relation to the information they can derive. The optimal combination of sensors is highly dependent on the context, the data requirements defined in Section 5, and the cost of the technology. As a fact, the choice of the sensing system highly depends on the cost of the technology. Municipalities have reported that specific radar systems are too costly and prefer induction loop sensors for permanent use. More expensive systems are typically used for temporary counts, however, it is less common for these technologies to be installed permanently. When accounting for costs a policymaker considers implementation costs, technology costs, maintenance and operation costs. Manual counts have a low technological cost but, in the long run, also may lead to high operational and data processing costs depending on the frequency and quantity of the data collection.

Depending on the application, the data can be used and not stored or stored for future assessments. If the storage is needed we have a data collection system if storage is not required we have a sensing system (strictly speaking). For example, a sensor for traffic control at the intersection collects data that is used directly, to give a cyclist green immediately if no conflicting traffic is present. The same data could be stored to see whether an intersection needs maintenance or improvement to the control systems. Some data collection techniques, like manual counts or surveys, are by default storing the data whereas others use digital sensors that do not necessarily store data. The type of data that are stored makes the systems more or less sensitive to privacy issues.

This section describes bicycle data collection systems contained in Table 1. The description of each data source will highlight the data requirements met (or not) by each sensor type and their limitations. For more details on emerging data sources for cyclists we refer the reader to Lee and Sener (2020) and Willberg et al. (2021), which are the most updated review at the time of writing this article.

- **Travel surveys:** are a traditional way of collecting travel data for transport demand modelling. They are still widely used when other contextual information (i.e. household demographics, trip purpose etc.) needs to be revealed, besides the trip itself. The purpose and way these surveys are conducted have evolved in recent years as described in Stopher and Greaves (2007) and Hoogendoorn-Lanser et al. (2015) and determines the frequency, accuracy, and representatives of this data collection system.
- **Manual counts:** are easy to implement and do not require expensive equipment. This is still the primary data collection technique in many places and is a good starting point to monitor cycling activity at specific locations for short durations of time (FHWA Federal Highway Administration, 2016). In bicycle emerging cities manual counts are of great value because they can spot anomalies and attributes of cyclists that the most advanced sensor can not detect. The downside is reliability, quality, and the labour cost of the observer. This data collection system has relatively cheap set-up costs, but in the long term can become labour-intensive and not salable for other software solutions such as demand-responsive intersections control. Therefore, manual counts can be a valid starting point for bicycle ignorant and emerging cities, but, once a city starts having higher flows or needs to have more long term counts it should consider

---

[8] Note that latency also depends on the way the data is stored and made available to the application: while an intersection controller may have ‘direct access’ to the sensors, many applications involving travel time data will poll the information from a server.

Table 1
Relation between main information type and data collection system. [a] two closely located sensors are needed to infer speeds. [b] occlusion errors have a negative influence on the estimation accuracy of this variable. [c] sensor can be placed at fixed location or on moving vehicles/bikes. [d] depends on the penetration of the technology in the population.

Data collectionInformation	Collisions	Conflicts	ODs	Trips	Position	Speed	Queue	Density	Flow	Age, Gender, Emotion
Travel surveys	☐	☐	■	■	☐	☐	☐	☐	☐	■
Manual counts	■	■	☐	☐	■	☐	■	☐	■	■
Push button	☐	☐	☐	☐	■	☐	☐	☐	☐	☐
Inductive loop sensor	☐	☐	☐	☐	■	■[a]	■[b]	■	■	☐
Infrared sensor	☐	☐	☐	☐	■	■[a]	■[b]	■	■	☐
Radar	☐	☐	☐	☐	■	☐	■	■	☐[d]	☐
WiFi/Bluetooth sensor	☐	☐	☐	☐	■	■[a]	■[d]	■[d]	■[d]	☐
GPS	☐	☐	☐	☐	■	■[a]	☐	■[d]	■[d]	☐
CDR mobile phones	☐	☐	■	■	☐	☐	☐	☐	☐	☐
Smart Camera	■	■[c]	☐	☐	■	■	■	■	■	■
Crowd sourced records	■	■	■	■	☐	☐	☐	☐	☐	☐

automatic data sources - especially if there are plans to implement dynamic traffic controllers for bicycles.

- **Push buttons** are sensors that cyclists need to push to activate. Once activated, the presence of a cyclist is detected. This can be used to activate the green light for their direction. The push-button can also estimate the waiting time of the first cyclist that presses the button, if a log of the timing of the traffic light is stored. The data it collects is not representative of the waiting time of all cyclists that pass the intersection, but only of the first cyclist that approaches the intersection.
- **Inductive loops** detect metal objects (bikes) passing on top of it. A bicycle passing over an inductive loop temporarily ‘occupies’ it, by changing the magnetic field of a loop, approximately from the moment the front of the bicycle is on the loop until when the rear wheel is out of the loop. This is the individual occupancy. If one uses two loops it is possible to calculate density from the flow and the mean of the local speeds. The level of the queue in front of a red light can also be estimated with two loops and some estimation techniques (Reggiani et al., 2019). The data collected by the loop sensors is potentially representative of all the cyclists passing the intersection (since it is not an in-vehicle device which would inevitably have a selection bias), however, occlusion errors, which appear when two or more cyclists pass on the sensor at the same time, affect the quality of the measurements.
- **Infrared sensors** can detect the presence of a cyclist and estimate speed, flow, and densities similarly to inductive loops. The disadvantage is that they are sensitive to bad weather and do not distinguish between cyclists and pedestrians.
- **Radar technology** can be used for different applications, including presence, density and queue length estimation. The quality of the data may be affected if there are multi-modal users (e.g. pedestrians, cyclists, cars).
- **Wi-Fi and Bluetooth technology** works depending on how many cyclists have an active Bluetooth or Wi-Fi connection on their personal devices. With these sensors, it is possible to identify the flow. Depending on the number of fixed sensors located in the city it is also possible to infer trips of travellers through the network. The network occupancy (approximation of densities) can be estimated via the total number of detections at each moment in time. Furthermore, queues and speeds can be derived based on signals from two closely located sensors. A limitation of these systems is that if it is an area with cyclists and pedestrians it is not trivial to identify mode-specific signals, this has consequences on the data quality.
- **GPS** data collection techniques, can track people with a longer range of travel time and distance. GPS can be collected via mobile phone apps or by specific GPS sensors installed on bikes (bike-sharing companies usually install them on their fleet). This is considered more intrusive since cyclists have to be equipped with sensors and give away privacy-sensitive data. When using this data source one must consider the representativity of the data, given the bias of who uses GPS systems.
- **Call Dial Records (CDR)** is location data collected by cellular carriers when a mobile phone connects to the cellular network. From call records in a city, there is the possibility, depending on the accuracy, to reconstruct trips and OD demand (Olmos et al., 2020). Privacy issues and frequency of the measurements should be considered when comparing this data collection system to others.
- **Smart cameras** work as normal cameras combined with data processing algorithms. They can estimate traditional traffic flow variables such as the waiting time for cyclists, speed, flow and queue length. More sophisticated systems can estimate demographics such as gender or age as well as perform facial recognition which can indicate emotion. The limitations of this technology are related to privacy issues, which make it challenging to implement and non-attractive to users, who often have a negative perception of cameras and surveillance-related sensors.
- **Crowd sourced records** can collect a wide amount and variety of data. Depending on the platform functionality, a wide variety of community needs can be detected. There are platforms to report obstacles and barriers, collisions or near misses, as well as the perceived safety of cyclists. For example in the city of Utrecht, there is a website where one can indicate dangerous places or malfunctioning traffic lights [9].

---

[9] https://www.utrecht.nl/wonen-en-leven/verkeer/verkeersprojecten/verkeerslichten/

7. Empirical evidence from bicycle friendly and dominant cities

In this section, we investigate the data collection and sensor systems deployed by Dutch municipalities and identify the uses of the systems. In the Netherlands, more than 25% of all trips is made by bicycle (National Institute for Public Health and the Environment, 2018). Based on the bicycle share of trips, kilometres cycled per inhabitant per day, and the fatality rates and non-fatal injury rates by distance travelled we can safely say that most of the cities in the Netherlands are bicycle-friendly (Pucher and Buehler, 2007). However, even among the Dutch cities, some are more friendly and others more bike dominant (i.e. with higher congestion and high flow issues). More information on the respondent cities is provided in Section 7.2.

The investigation shows common practices in bicycle-friendly and dominant cities. We focus on network intersections since these are the locations that predominantly affect network bikeability and where the Dutch municipalities have focused efforts in terms of data collection systems. The steps in the investigation were: 1) identify what data collection systems are deployed at interSections 2) what type of information is extracted from the data, and what software solutions are implemented based on the gained information. This empirical evidence, linked to the theoretical framework allows for an understanding of which levels of BNNs are being fulfilled. Moreover, by looking at the deployed sensors and solutions implemented we can identify if the sensors are used to their full capacity.

The secondary aim of this survey is to shed light on the deployed bicycle sensors in bicycle-friendly and dominant cities. The survey provides an unprecedented inventory of bicycle sensors used at major intersections. As a fact, it is not well known if the Dutch municipalities pose considerable attention to their bicycle sensor infrastructure, besides the well-integrated bicycle network infrastructure. Given the limited information that is available on best practices for monitoring non-motorized traffic (FHWA Federal Highway Administration, 2016), this empirical evidence also serves as knowledge (and best-practices) sharing between bike-friendly/ dominant cities, researchers, and city planners worldwide.

7.1. Survey design

The survey was intended for experts that have knowledge on the use of bicycle sensors by Dutch municipalities. That constrained the respondent selection to Dutch municipality employees and consultants who work with and advise Dutch municipalities. The survey was directly sent to the members of Contact group Traffic Control Technicians Netherlands (Contactgroep Verkeersregeltechnici Nederland) and Traffic Control Technicians initiative (Initiatiefgroep Verkeersregeltechnici) and to some employees of SWECO, an engineering consultancy with experience in bicycle traffic control in the Netherlands, on the 19th of May, 2020. Next to this, the survey was posted on LinkedIn (a professional networking social media platform).

To keep the survey short and straightforward (so that respondents answer all questions) the study investigated six specific sensing technologies: push buttons, loop sensors, infrared sensors, Wi-Fi/Bluetooth sensors, smart cameras and mobile applications that can track cyclists. The first three sensors were chosen because they are considered to be the most common bicycle sensors in the Netherlands. The last three sensors were chosen as they belong to the group of new and innovative sensors, that have the potential to become more common in the future.

7.2. Survey respondents

The survey was closed on the 9th of June, 2020, having collected fifteen responses in 21 days. We linked individual respondents to the city or consultancy in which they worked (the survey explicitly asked to which city their answers related to). The municipality or consultants that responded to the survey are: *Eindhoven, Delft, Haarlemmermeer, Leiden, Almere, 's-Hertogenbosch, Den Haag, Utrecht, Amsterdam, Enschede, Haarlem, Overijssel (province), Zuid-West x(Rijkswaterstaat), Vialis, Witteveen + Bos.*

Information about the respondent municipalities/regions can be found in Table 2, including their number of inhabitants, surface area, bike share and cycling score. Clearly distinguishing which cities are bike dominant or friendly cannot be achieved easily without in-depth investigation on bicycle mobility citywide. However, a useful tool to have a rough indication of the bike culture within a city in the Netherlands is provided by the annual bicycle score assigned by the cycling union of the Netherlands (Fietsersbond, 2020), to which we refer the reader. We finally underline how other classifications of cities are possible and may differ based on the context, time of day, and the data collection method.

Together, the municipalities that responded are 3.7% of all Dutch municipalities yet they represent 17.8% (3 006 375 residents) of total Dutch inhabitants. All responding cities are considered large municipalities (with over 100 000 inhabitants) the cities that responded make up 11 out of 24 of the larger municipalities in the Netherlands. All the municipalities are considered to be *bike-friendly or -dominant* cities, with the distinction in classification dependent on the street and time of day.

The respondents are considered to be representative of the major municipalities not of the whole Netherlands. The two types of bias we identify are: 1) larger cities responded more than smaller ones and 2) inevitably cities that have a wide deployment of sensors are more inclined to respond than ones that don't have any sensors. Some respondents answered on behalf of the province of Overijssel and the South-West region of the Netherlands (Rijkswaterstaat VCZWN). Within these areas, there are smaller municipalities, yet those responses are too generic to attribute these results to smaller municipalities. Conclusions based on the survey therefore should be drawn with caution. Meaning that the results may refer to the best-equipped cities in terms of bicycle sensors and data collection systems.

7.3. Survey results

This section reports the main results from the survey and reflects on the extent to which the framework is implemented in practice.

7.3.1. Deployed sensors and data collection systems

Fig. 4 shows that all responding municipalities stated that 80%-100% of all their signalised intersections are equipped with inductive loop sensors and push buttons. Two respondents, out of fifteen, stated that 80%-100% of all their signalised intersections are equipped with mobile

Table 2
Information about municipalities or areas that participated in the survey. Mode share was gathered from the Fietsberaad (Fietsberaad, 2010). The cycling score was retrieved from the cycling union of the Netherlands (Fietsersbond, 2020).

Municipality or area	Number of inhabitants	Surface area [km^2]	Bike trip share [%]	Cycling score [1 to 5]
Eindhoven	231 469	88.84	22	3.4
Delft	103 163	24.06	26	3.4
Haarlemmermeer	154 235	206.31	15	3.2
Leiden	124 899	23.27	31	3.4
Almere	207 904	248.77	19	3.4
's-Hertogenbosch	110 790	39.98	18	3.7
Den Haag	537 833	98.13	18	3.3
Utrecht	352 866	99.21	20	3.4
Amsterdam	862 965	219.49	21	2.9
Enschede	158 986	142.72	25	4.1
Haarlem	161 265	32.09	24	3.2
Overijssel (province)	1 156 431	3 420.74	–	–
Zuid-West (Rijkswaterstaat)	–	–	–	–

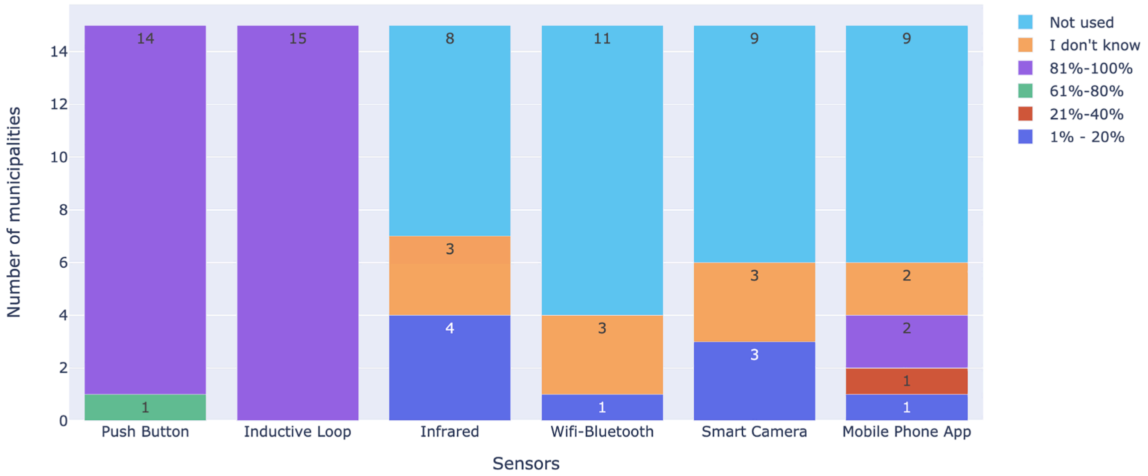


Fig. 4. Percentage of intersections equipped with the various kinds of bicycle sensors.

phone-Bluetooth technology. Whereas, two cities reported between 1%-40% of all their signalised intersections to be similarly equipped. Three cities, out of fifteen, stated that between 1%-20% of all their signalised intersections are equipped with smart camera technology. Infrared and WiFi/Bluetooth technology has a lower adoption rate. Answers from the survey made clear that the most popular inductive loop sensor configuration is 2 or 3 sensors per direction. Having two or more sensors allows for the extraction of speed information, whereas one sensor can only measure flow. Only four cities out of fifteen reported having one sensor per direction as the most popular configuration.

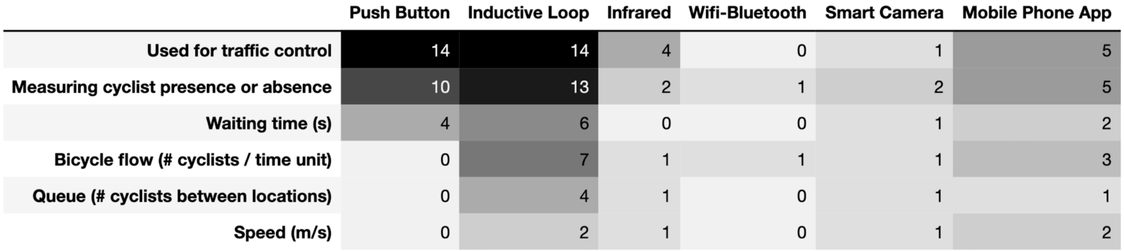
7.3.2. *Derived information and applications*

Fig. 5 summarises the information being extracted from the deployed sensors. The main action being taken upon bicycle detection systems in the Netherlands is automatic traffic control. All cities reported using vehicle-actuated traffic control but only one reported storing the data. Loop sensors, similarly to push buttons, are predominantly used for vehicle-actuated traffic control. Half of the respondents stated that they use loop sensors for flow, queue and waiting time estimation. Only two respondents, out of fifteen, reported estimating speeds. Mobile applications are mainly used for traffic control purposes, and to a lesser extent for flow, speed, waiting time and queue estimation. Smart cameras are used by one city for traffic control, as well as flow, queue, speed, and waiting time estimation. When asked if the municipalities are aware of being able to estimate certain variables, with the raw data they currently collect, yet not using them, two-thirds of the respondents said they were aware. However, when asked what additional variables they could collect, not all variables were always listed, indicating that there is some knowledge lacking.

7.3.3. *How much of the framework logic is implemented?*

To close the circle of reasoning, let us go from empirical evidence back to the theorized framework. Based on the results, it is remarkable to notice that almost all signalised intersections in the Netherlands have some kind of detection sensors for bikes, mainly for traffic control purposes. Based on the theorized framework, cities in the Netherlands are facing ‘bike-friendly’ and ‘bike-dominant’ needs. The results from the survey give an example of what bicycle-friendly and dominant cities focus on, it turns out that these cities are involved in developing solutions to deal with comfort and congestion. The main implemented solution, is bicycle-actuated traffic control, which addresses bike-friendly and dominant needs, such as travel time, comfort, and to a smaller extent also safety, showcasing cities higher up in the pyramid of bicycle network needs. Although vehicle-actuated traffic control is a well-established reality in the Netherlands, from our understanding, it is not based on speed nor the number of queued cyclists but the presence of one or more cyclists. The additional information could be used to implement more advanced solutions in bike dominant contexts. The survey shows that the sensor technology to estimate speed and number of cyclists is already being deployed (see Table 1) and that cities should develop new state estimation and processing techniques to capture this information. The proposed need-driven framework leads to a more systematic approach to identifying needs-solutions-information. Such a systematic approach helps in better exploiting the sensors, by identifying more information to extract in order to implement other solutions.

The results of the survey show that ICT sensing technology is abundant in all signalised intersections of major cities in the Netherlands in contrast to the small amount of derived information. For example, three municipalities are starting to employ smart cameras however, the survey did not show new employment of the data coming out from the cameras. Having a structured framework as we propose, would avoid redundancy in sensors and make sure that all additions to the data collection system enable derivation of novel information. Notwithstanding the importance of the findings, the survey is not without limitations. The survey results



	Push Button	Inductive Loop	Infrared	Wifi-Bluetooth	Smart Camera	Mobile Phone App
Used for traffic control	14	14	4	0	1	5
Measuring cyclist presence or absence	10	13	2	1	2	5
Waiting time (s)	4	6	0	0	1	2
Bicycle flow (# cyclists / time unit)	0	7	1	1	1	3
Queue (# cyclists between locations)	0	4	1	0	1	1
Speed (m/s)	0	2	1	0	1	2

Fig. 5. Current information derived from deployed sensors at intersections. Mobile phone apps mainly work with GPS technology and when connected to traffic lights can request green as a cyclists is approaching.

should be interpreted with caution because there might be a miss-alignment between the survey designer posing a question and what the respondent understands. Future research could consider semi-structured interviews with municipalities, as this would allow researchers to gain direct feedback on the understanding of the question from the respondents. More qualitative research should be carried out with a broader range of experts (also with experts outside the traffic controller domain), to gain more certainty on what actions are implemented based on the derived data.

8. Empirical evidence from bicycle ignorant city

In his section, we report the common practices of cities with lower levels of bicycle culture. As an example of a bicycle ignorant/emerging city, we refer to a case study in Melbourne Australia. Melbourne has bike trip share of 2% which shows some signs of bicycle use (so it is more than a bicycle hostile city) but still, the trip bike share is at low levels compared to other cities (Pucher and Buehler, 2007). Moreover, a study revealed that traffic-related fatality and serious injury rates per kilometre travelled for cyclists in Melbourne are high in comparison with private motor vehicle occupants (Garrard et al., 2010). For these reasons, we consider Melbourne as a bicycle-ignorant city reaching towards a bicycle-emerging culture.

Through the analysis of the strategic cycling plans developed by the City of Melbourne (2015), we can identify the type of data collection systems currently being used and the information derived from these systems to develop network solutions. Through this case study, common practices of a bicycle ignorant city are identified, while the benefits of the proposed BNN framework are highlighted. The focus of data collection in Melbourne and cities with similar LoBC is on infrastructure, parking, safety and facilitating connections to activity locations such as schools and shops (City of Melbourne, 2015). This section presents the data collection systems and information used in such cities to highlight their alignment with the proposed framework.

8.1. Data collection systems

Manual records of crashes involving cyclists are among the primary data collection systems in place in Melbourne. Police reported events are manually recorded and stored in an online database (Road Crash Information System (RCIS)). Hospital admissions and Emergency Department presentations are also reported. However, there are well-documented limitations with each of these data collection methods due to under-reporting, particularly of minor crashes and bicycle only cases (Boufous et al., 2013). Melbourne has a well-established household travel survey, which is used to monitor cycling participation and travel behaviour (Victorian Government, 2021). The data collection systems in household travel surveys are not specific to cycling, and collect information on all travel behaviour. While they do indicate mode share and user preferences, there are noted limitations due to sample size which limit data to aggregate analysis. Increasingly, manual counts of bike flow are being initiated across Australian cities (Bicyclenetworkcom, 2021). Events such as the one day ”Super Tuesday” count are carried out by volunteers from cycling advocacy groups and provide a snapshot of cycling by collecting data along major cycling corridors and at key intersections (Bicyclenetworkcom, 2021). Inductive loop sensors represent somewhat of a novelty in bicycle ignorant cities. Melbourne has recently installed 12 inductive loops at key locations, increasing the network to 42 off-road and 4 on-road detection sites (Victorian Government, 2021). Bicycle inclusive cities aim to involve the community of cyclists to listen and fulfil their needs. For this reason, it is common to have a crowdsourced platform to report network failures and infrastructure improvement possibilities (Conrow et al., October 2017). Finally, phone applications are used by some cities to log cyclist trips. The representatives of these data need to be taken into consideration, as most cyclists may not log all their trips, or only log longer trips more commonly associated with recreational riding (Jestico et al., 2016).

8.2. Derived information and use

The information that is captured in the aforementioned data collection systems in Melbourne pertain to safety and network improvements. Namely, the deployed data collection systems aim to identify unsafe locations, travel behaviour and bike use, missing connections in the bicycle network and improve parking needs. This information is used to develop and improve the physical infrastructure network (hardware solutions). This suggests that a city like Melbourne can be classified as an ignorant cycling city (in accordance with the framework presented in Section 2), in that it strives to meet ignorant bicycle needs. The case study of Melbourne highlights the large amount of manual data collection which a bicycle ignorant city relies on. Manual counts in particular open debate on the objectivity of measurement. For cities that aim to reach a medium or high bicycle mode share, there is a need to have a long term and comprehensive overview of its bicycle networks, the needs of cyclists and solutions to address these needs. The framework presented in this manuscript aids in planning the data collection system that is required to meet the current and near-future needs of a city. The framework offers insight into the use and benefits of various automated data collection systems that provide objective measurement, which can be used for before and after evaluation of infrastructure and used to measure later stages of bicycle culture.

9. Discussion

The results of the survey and case study, linked to the theoretical framework and findings from previous works, allow us to showcase our framework. While bicycle ignorant and emerging city contexts have been widely studied in terms of network growth strategies and data collection systems, it was not known how bike-friendly and dominant cities make use of their sensors and data sources. In this section, we discuss the findings and suggest that the need-driven framework is a useful guide for bicycle network performance improvement.

In bike-ignorant and emerging cities data collection usually is not on the top priority of mobility commissions. These types of cities prioritise building fast and within budget bike lanes and neglect to plan a before and after intervention data collection plan (Mölenberg et al., 2019). However, these cities could highly benefit from data collection on the usage of the infrastructure and travel behaviour to prove the need for such space reallocation and investments. In Melbourne, this could involve investment in detection technology when new bicycle lanes are constructed, or intersections are upgraded. Bicycle ignorant cities focus on safety, origin–destination and trip data in order to create a strategic starting point for their cycling network (Silva et al., August 2018; Lovelace et al., 2017). Only a few started to monitor flows, but not with automated sensors.

The survey carried out in the Dutch municipalities showed that in bike-friendly and dominant cities the collected data is mainly the presence of a cyclist. This is easy to measure with loop sensors and is the basic input for vehicle-actuated traffic controllers. Only a few municipalities estimate flows, waiting times, queues, and speeds at intersections. The reason for estimating only presence and not other traffic variables can be related to the higher data processing complexity, inaccuracy of loop sensors (e.g. errors due to occlusion), and a lack of knowledge on how to apply the new information. Although there are new sensing technologies deployed at intersections, as reported from the survey (e.g. mobile phone apps and smart cameras) the information extracted from these systems is the same as what is obtained from more traditional types of sensors, resulting in an underutilization of the new sensors. One limitation to the development of more advanced data applications evolving from smart camera data could be due to privacy issues. Thus more research is needed on privacy-preserving systems to fulfil new BNNs of municipalities.

Finally, the Netherlands is a bike-friendly nation (in certain places bike dominant) that is starting to face congestion problems on the bicycle network (City of Delft, 2019). This may suggest that one day, bicycle ignorant cities, like Melbourne, that are stimulating cycling today, will need to deal with the same issues the Netherlands is currently facing. Moreover, the recent Covid-19 pandemic has created a surge in cycling in cities and people transition to cycling rather than take crowded public transport (Kraus and Koch, 2020) and also increasingly engage in cycling as a recreational activity. This has seen cities needing to fulfil bike network needs faster than expected, particularly through “pop-up” infrastructure. However, this rapid increase in cycling hardware often occurs without planning and implementing the required software for data collection in accordance with the BNNs. The *first-mover disadvantage* theory suggests that other emerging cities can benefit, without necessarily copying, from the Netherlands. To this end, results from the survey should be interpreted with caution and each city should use the need-driven framework to identify its optimal combination of data collection systems as opposed to installing the same sensors deployed in Dutch cities.

10. Conclusion

In this paper, we proposed a *need-driven framework* which helps municipalities and research communities in identifying what sensor or data collection systems should be deployed based on the level of bike culture of a city (pyramid of needs). Via the pyramid of needs, cities can identify solutions and bicycle data collection systems that can improve their network performance (e.g. via design adaptation, deployment of traffic management schemes, ICT, mobility service provision such as share bicycles). Rather than using a technology-push approach, in which popular or easy to install technology is deployed, cities should follow a need-driver approach as suggested by the framework so to meet their bicycle network needs and make efficient use of resources.

Empirical evidence from the Netherlands and Australia reflects the logic of the framework, albeit further research is needed to explore hostile and ignorant cities. Previous works have reported that bicycle ignorant and emerging cities focus on origin–destination and trip data in order to develop a strategic starting point for their cycling network (Silva et al., August 2018; Lovelace et al., 2017) and this is confirmed when reviewing literature from Melbourne. Whereas the survey to the Dutch cities shows that bicycle-friendly and dominant cities focus on comfort and congestion needs and collect different types of data, related to the real-time use of the network and its intersections. Results from the survey show that the main municipalities in a bike-friendly country use intersection sensing technology mainly for real-time bicycle-actuated traffic control, which we argue is a means to improve comfort - especially when bicycles are prioritized over other modes of transport.

This systematic overview on network needs, solutions, information, data requirements, sensors and data collection systems contributes to 1) identifying a starting point for data collection in bicycle-ignorant cities, 2) improving the synergy between needs and data collection systems, 3) using the deployed technology at its full capacity and 4) developing better traffic management solutions for bike dominant type of cities, based on (potentially) available data.

11. Funding

This research was supported by the ALLEGRO project, which is financed by the European Research Council (Grant Agreement No. 669792) and the Amsterdam Institute for Advanced Metropolitan Solutions.

Availability of data and material

Not applicable.

CRediT authorship contribution statement

Giulia Reggiani: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft, Project administration. **A. Maria Salomons:** Supervision, Conceptualization, Investigation, Writing - review & editing. **Merel Sterk:** Investigation, Formal analysis. **Yufei Yuan:** Supervision, Validation, Writing - review & editing. **Steve O’Hern:** Validation, Writing - review & editing. **Winnie Daamen:** Supervision. **Serge Hoogendoorn:** Supervision, Methodology, Writing - review & editing, Funding acquisition.

CRediT authorship contribution statement

Giulia Reggiani: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft, Project administration. **A. Maria Salomons:** Supervision, Conceptualization, Investigation, Writing - review & editing. **Merel Sterk:** Investigation, Formal analysis. **Yufei Yuan:** Supervision, Validation, Writing - review & editing. **Steve O’Hern:** Validation, Writing - review & editing. **Winnie Daamen:** Supervision. **Serge Hoogendoorn:** Supervision, Methodology, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was supported by the ALLEGRO project, which is financed by the European Research Council (Grant Agreement No. 669792) and the Amsterdam Institute for Advanced Metropolitan Solutions.

References

Behrendt, F., 2016. Why cycling matters for Smart Cities. Internet of Bicycles for Intelligent Transport. J. Transp. Geogr. 56, 157–164. https://doi.org/10.1016/j.jtrangeo.2016.08.018.

Bicyclenetworkcom, 2021. Super counts – bicycle data.https://www.bicyclenetwork.com.au/our-services/transport-surveys-and-data/super-counts/.

Boufous, S., de Rome, L., Senserrick, T., Ivers, R.Q., 2013. Single- versus multi-vehicle bicycle road crashes in Victoria, Australia. Injury Prevention 19 (5), 358–362. https://doi.org/10.1136/injuryprev-2012-040630.

Buehler, R., Dill, J., 2016. Bikeway Networks: A Review of Effects on cycling. Transp. Rev. 36 (1), 9–27.

Centre for Public Impact, 2016. Green Waves for bicycles in Copenhagen-Centre for Public Impact. https://www.centreforpublicimpact.org/case-study/green-waves-bicycles-copenhagen/, url: https://www.centreforpublicimpact.org/case-study/green-waves-bicycles-copenhagen/.

City of Melbourne, 2015. Melbourne bicycle plan2016-2020.pdf.https://www.melbourne.vic.gov.au/parking-and-transport/cycling/Pages/bicycle-plan.aspx.

Conrow, L., Wentz, E., Nelson, T., Pettit, C., October 2017. Comparing spatial patterns of crowdsourced and conventional bicycling datasets. Appl. Geogr. 92, 21–30. https://doi.org/10.1016/j.apgeog.2018.01.009.

CROW, 2017. Design manual for bicycle traffic.

Dabiri, A., Hegyi, A., Hoogendoorn, S., 2019. Automatic learning of cyclist’s compliance for speed advice at intersections - a reinforcement learning-based approach. 2019 IEEE Intelligent Transportation Systems Conference, ITSC 2019, 2375–2380. https://doi.org/10.1109/ITSC.2019.8916847.

De Angelis, M., Stuiver, A., Fraboni, F., Prati, G., Puchades, V.M., Fassina, F., de Waard, D., Pietrantoni, L., November 2018. Green wave for cyclists: Users’ perception and preferences. Appl. Ergon. 76, 113–121. https://doi.org/10.1016/j.apergo.2018.12.008.

De Groot-Mesken, J., Vissers, L., Duivenvoorden, K., 2015. SWOV-Gebruikers van het fietspad in de stad. Tech. rep., SWOV.

City of Delft, 2019. Bicycle Flows – SCIFI Smart City Innovation Framework Implementation. http://smartcityinnovation.eu/open-calls/bicycle-flows/, url: http://smartcityinnovation.eu/open-calls/bicycle-flows/.

Ehrgott, M., Wang, J.Y., Raith, A., Van Houtte, C., 2012. A bi-objective cyclist route choice model. Transp. Res. Part A: Policy Practice 46 (4), 652–663. https://doi.org/10.1016/j.tra.2011.11.015.

FHWA Federal Highway Administration, 2016. Traffic monitoring guide. Tech. rep., U.S. Dept. of Transportation, Washington, DC., url: http://www.fhwa.dot.gov/policyinformation/tmguide/.

Fietsberaad, 2010. Figures on bicycle use per municipality. https://www.fietsberaad.nl/Kennisbank/Cijfers-over-fietsgebruik-per-gemeente, url: https://www.fietsberaad.nl/Kennisbank/Cijfers-over-fietsgebruik-per-gemeente.

Fietsersbond, 2020. Cycling city 2020: How does you municipality score?https://www.fietsersbond.nl/fietsstad2020/fietsstad-2020-hoe-scoort-jouw-gemeente/.

Garber, M.D., Watkins, K.E., Kramer, M.R., 2019. Comparing bicyclists who use smartphone apps to record rides with those who do not: Implications for representativeness and selection bias. J. Transp. Health 15 (October), 100,661. https://doi.org/10.1016/j.jth.2019.100661.

Garrard, J., Greaves, S., Ellison, A., 2010. Cycling injuries in Australia: Road safety's blind spot? J. Austr. College Road Saf.

Grossman, A., Rodgers, M.O., Xu, Y., Guensler, R., Watkins, K., 2019. If Safety Matters. Let's Measure It: Nationwide Survey Results for Bicycle and Pedestrian Treatment Prioritization. https://doi.org/10.1061/jtepbs.0000205.

Hiddink, R., Hoogendoorn, S., Pel, A., Annema, J., Adams, K., 2017. Evaluation of Urban Transport Policy:Development of an approach to express and measure policy goals in traffic networks in Dutch cities. Msc thesis, TU Delft.

Hoogendoorn-Lanser, S., Schaap, N.T., Oldekalter, M.J., 2015. The netherlands mobility panel: an innovative design approach for web-based longitudinal travel data collection. Transp. Res. Procedia 11, 311–329. https://doi.org/10.1016/j.trpro.2015.12.027.

Jestico, B., Nelson, T., Winters, M., 2016. Mapping ridership using crowdsourced cycling data. J. Transp. Geogr. 52, 90–97. https://doi.org/10.1016/j.jtrangeo.2016.03.006.

Kazemzadeh, K., Laureshyn, A., Hiselius, L.W., Ronchi, E., 2020. Expanding the scope of the bicycle level-of-service concept: A review of the literature. doi:10.3390/su12072944.

Kraus, S., Koch, N., 2020. Effect of pop-up bike lanes on cycling in European cities. arXiv pp 1–19, url:http://arxiv.org/abs/2008.05883, 2008.05883.

Lee, K., Sener, I.N., 2020. Emerging data for pedestrian and bicycle monitoring: Sources and applications. Transp. Res. Interdisc. Perspect. 4 (100), 095. https://doi.org/10.1016/j.trip.2020.100095.

Lovelace, R., Goodman, A., Aldred, R., Berkoff, N., Abbas, A., Woodcock, J., 2017. The propensity to cycle tool: An open source online system for sustainable transport planning. J. Transp. Land Use 10 (1), 505–528. https://doi.org/10.5198/jtlu.2016.862, 1509.04425.

Maslow, A.H., 1943. A theory on human motivation. Psychol. Rev. 50, 370–396.

McLeod, S., Babb, C., Barlow, S., 2020. How to 'do' a bike plan: Collating best practices to synthesise a Maturity Model of planning for cycling. Transp. Res. Interdisc. Perspect. 5 (100), 130. https://doi.org/10.1016/j.trip.2020.100130.

Mölenberg, F.J., Panter, J., Burdorf, A., Van Lenthe, F.J., 2019. A systematic review of the effect of infrastructural interventions to promote cycling: Strengthening causal inference from observational data. Int. J. Behav. Nutr. Phys. Activity 16 (1). https://doi.org/10.1186/s12966-019-0850-1.

Muller, T.H., De Leeuw, M., 2006. New method to design traffic control programs. Transp. Res. Rec. 1978, 68–75. https://doi.org/10.3141/1978-11.

National Institute for Public Health and the Environment, 2018. Cycling in the Netherlands. https://crowplatform.com/wp-content/uploads/Cycling-in-the-netherlands.pdf, url: https://crowplatform.com/wp-content/uploads/Cycling-in-the-netherlands.pdf.

Nikolaeva, A., te Brömmelstroet, M., Raven, R., Ranson, J., 2019. Smart cycling futures: Charting a new terrain and moving towards a research agenda. J. Transp. Geogr. 79 (July), 102,486. https://doi.org/10.1016/j.jtrangeo.2019.102486.

Olmos, L.E., Tadeo, M.S., Vlachogiannis, D., Alhasoun, F., Espinet Alegre, X., Ochoa, C., Targa, F., González, M.C., 2020. A data science framework for planning the growth of bicycle infrastructures. Transp. Res. Part C: Emerging Technol. 115 (January), 102640. https://doi.org/10.1016/j.trc.2020.102640.

Oosterhuis, H., 2013. Bicycle Research between Bicycle Policies and Bicycle Culture. Mobility in History 5 (1), 20–36. https://doi.org/10.3167/mih.2014.050103.

Orozco, L.G.N., Battiston, F., Iñiguez, G., Szell, M., 2020. Data-driven strategies for optimal bicycle network growth. R. Soc. Open Sci. 1907, 07080.

Pelzer, P., 2010. Bicycling as a Way of Life: A Comparative Case Study of Bicycle Culture in Portland, OR and Amsterdam. 7th Cycling and Society Symposium (September): 1–13, url: http://www.tsu.ox.ac.uk/events/100906/css-pelzer-paper.pdf.

Pogačar, K., Dežan, L., Lamot, M., Renčelj, M., 2020. Determinants of bicycle use among student population: Exploratory research of social and infrastructure factors. Appl. System Innov. 3 (1), 1–17. https://doi.org/10.3390/asi3010006.

Pucher, J., Buehler, R., 2007. Making cycling irresistible: Lessons from the Netherlands, Denmark, and Germany. Transp. Rev. 28(4):495 – 528, doi:10.1080/01441640701806612, url:https://doi.org/10.1080/01441640701806612.

Reggiani, G., Dabiri, A., Daamen, W., Hoogendoorn, S., 2019. Clustering-based methodology for estimating bicycle accumulation levels on signalized links: a case study from the Netherlands. 2019 IEEE Intelligent Transportation Systems Conference, ITSC 2019, 1788–1793. https://doi.org/10.1109/ITSC.2019.8917138.

Rupi, F., Poliziani, C., Schweizer, J., 2019. Data-driven Bicycle Network Analysis Based on Traditional Counting Methods and GPS Traces from Smartphone. ISPRS Int. J. Geo-Inform. 8 (8), 1–16. https://doi.org/10.3390/ijgi8080322.

Salomons, A.M., 2020. Corona-safe' Measures for cyclists at intersections. arXiv pp 1–8, 2012.01488.

Sayed, T., Zaki, M.H., Autey, J., 2013. Automated safety diagnosis of vehicle-bicycle interactions using computer vision analysis. Saf. Sci. 59, 163–172. https://doi.org/10.1016/j.ssci.2013.05.009.

Silva, C., Teixeira, J., Proença, A., Bicalho, T., Cunha, I., Aguiar, A., August 2018. Revealing the cycling potential of starter cycling cities: Usefulness for planning practice. Transp. Policy 81, 138–147. https://doi.org/10.1016/j.tranpol.2019.05.011.

Song, M., Wang, K., Zhang, Y., Li, M., Qi, H., Zhang, Y., 2020. Impact evaluation of bike-sharing on bicycling accessibility. Sustainability (Switzerland) 12 (15). https://doi.org/10.3390/su12156124.

Stopher, P.R., Greaves, S.P., 2007. Household travel surveys: Where are we going? Transp. Res. Part A: Policy Practice 41 (5), 367–381. https://doi.org/10.1016/j.tra.2006.09.005.

Victorian Government, 2021. Bicycle volume and speed.https://discover.data.vic.gov.au/dataset/bicycle-volume-and-speed.

Watson, A., Watson, B., Vallmuur, K., 2015. Estimating under-reporting of road crash injuries to police using multiple linked data collections. Accident; analysis and prevention pp 18–25, doi:10.1016/j.aap.2015.06.011.

Wierbos, M.J., Knoop, V.L., Bertini, R.L., Hoogendoorn, S.P., 2021. Influencing the queue configuration to increase bicycle jam density and discharge rate: An experimental study on a single path. Transp. Res. Part C: Emerging Technol. 122(October 2020): 102,884, doi:10.1016/j.trc.2020.102884, url:https://doi.org/10.1016/j.trc.2020.102884.

Willberg, E., Tenkanen, H., Poom, A., Salonen, M., Toivonen, T., Ben-elia, E., Bartana, I. B., Cadima, C., Campisi, T., Dane, G., Freudendal-pedersen, M., Hamidi, Z., Heiska, I., Hagen, O.H., Klingen, J., Kostiainen, E., Krisp, J.M., Krizek, K., Larrodé, E., Hostis, L., Chardon, C.M.D., Nikolaeva, A., Nello, S., Pappers, J., Pritchard, J., Pritchard, R., Uteng, T.P., Radzimski, A., Raninen, M., Raun, J., Arroyo, G.R., Rupi, F., Saluveer, E., Skov-petersen, H., Tampieri, G., Tarkowski, M., Tarnanen, A., Teixeira, J.F., 2021. Comparing spatial data sources for cycling studies – a review. SocArXiv. https://doi.org/10.31235/osf.io/ruy3j.

Winters, M., Davidson, G., Kao, D., Teschke, K., 2011. Motivators and deterrents of bicycling: Comparing influences on decisions to ride. Transportation 38 (1), 153–168. https://doi.org/10.1007/s11116-010-9284-y.