

ORIGINAL ARTICLE

Automated Detection of Missing Links in Developed Bicycle Networks

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Cycling is an effective solution for making urban transport more sustainable. However, bicycle networks are typically developed in a slow, piecewise process that leaves open a large number of gaps, even in well developed cycling cities like Copenhagen. Here, we develop the IPCC procedure (Identify, Prioritize, Cluster, Classify) for finding the most important missing links in developed urban bicycle networks, by analyzing street networks from OpenStreetMap. We apply the IPCC procedure to Copenhagen and report the 105 top priority gaps. For evaluation, we compare these gaps with the city's most recent Cycle Path Prioritization Plan and find considerable overlaps. Our results show how network analysis with minimal data requirements can serve as a cost-efficient support tool for bicycle network planning. The IPCC procedure takes into account the whole city network for consolidating urban bicycle networks and can therefore well complement localized, manual planning processes, providing a data-driven framework for more effective, city-wide decision-making.

KEY WORDS

network analysis, bicycle network, sustainable mobility, urban data science, OpenStreetMap, urban planning

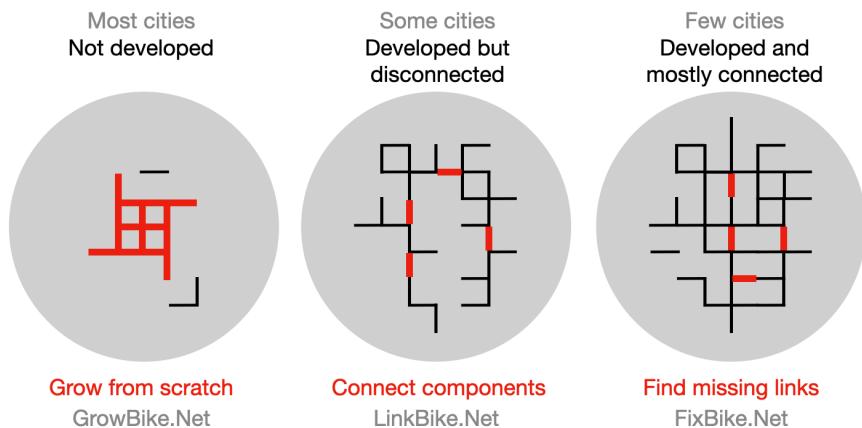


FIGURE 1 Depending on a city's existing bicycle network structure, different development approaches are adequate. Left: The approach of growing from scratch by Szell *et al.* (2021) is best applicable for underdeveloped cities, such as Los Angeles. See also: <https://growbike.net>. Center: The approach of Natera Orozco *et al.* (2020) to connect disconnected components can well fit cities that have developed but disconnected components, such as Budapest. See also: <http://linkbike.net>. Right: Here we develop a process for finding missing links also within a connected component, complementing the previous approaches. This method is best applicable to cities with a both well developed and connected network such as Copenhagen. See also: <http://fixbike.net>.

Introduction

In the face of increasing urbanization — with two thirds of the global population projected to live in cities by 2050 (United Nations Department of Economic and Social Affairs, 2018) — and of transport being one of the most problematic sectors in terms of emission reductions (Lamb *et al.*, 2021), urban transportation systems play a decisive role in tackling the climate crisis. There is enormous potential to be harnessed by “greening” the transportation sector through a modal shift towards active and more sustainable mobility modes such as cycling and walking, both in terms of climate change mitigation and socioeconomic benefits (Gössling *et al.*, 2019; High-level Advisory Group on Sustainable Transport, 2016).

In practice, however, bicycle infrastructure development struggles with a particularly pervasive political inertia due to the complex interdependencies of car-centrism (Mattioli *et al.*, 2020; Feddes *et al.*, 2020). Very few cities on the planet have so far managed to build up adequate, i.e. safe and cohesive (de Groot, 2016), bicycle networks. Notable best practice examples are found in the Netherlands and Denmark. However, even in the case of Copenhagen, despite over a century of political struggles and coordinated efforts to develop a functioning grid of protected on-street bicycle networks (Carstensen *et al.*, 2015), the city's bicycle network is far from being ideal. For example, its network of protected bicycle infrastructure is split into 300 disconnected components (Natera Orozco *et al.*, 2020) and its accessibility displays considerable local variations (Rahbek Vierø, 2020). Given that even the best urban bicycle networks on the planet are not perfect, it is natural to ask: “Where are the missing links?”, “How to fix them?”, and “How much will this cost and benefit the city?” These are the questions we aim to answer in this paper. Our approach is based on Vybornova (2021) to develop a generally applicable, computational procedure for finding missing links in developed bicycle networks, and testing it on the case of Copenhagen.

From a research perspective, a structured, data-driven approach to bicycle network planning, along with a strong theoretical and computational underpinning, is largely missing, but could be important for an evidence-based modal

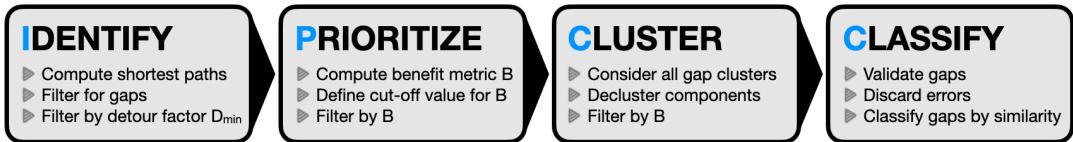


FIGURE 2 Steps in the IPCC procedure. Gaps are first identified via shortest paths, discarding parallel paths using a minimum detour factor D_{\min} . Gaps are then prioritized via a gap closure benefit metric, in the simplest case based on betweenness centrality. Resulting gaps can overlap (cluster) and need to be declustered. Finally, gaps are compared with existing infrastructure, validated or discarded, and classified.

shift towards sustainable urban transport systems due to increased bicycle use and reduced car use (Koglin and Rye, 2014; de Groot, 2016; Resch and Szell, 2019; Priya Uteng and Turner, 2019). The academic literature on bicycle network planning can be divided into two broad categories. The larger, first category contains transport planning papers with a *place-specific* focus. These case studies focus on improving the bicycle infrastructure of one particular city, for example Montreal (Boisjoly et al., 2020), Seattle (Lowry and Loh, 2017), or recent data-driven approaches for Bogotá (Olmos et al., 2020) or London (Palominos et al., 2021). Characteristic for these approaches is the specific application to one city and its idiosyncrasies, using a variety of data sets, such as orography, traffic flows, trip tables or citizen surveys on mobility preferences. In principle, this means there can be as many approaches as there are cities. The second, more recent approach, is based on the physics-inspired Science of Cities (Batty, 2013) and aims to identify the generalized laws and mechanisms that govern urban development and are *independent of place*. Typical of these approaches is the focus on the most important “first-order” effects following the paradigm of network science, sacrificing specificity for generality, therefore deliberately using maximally simplified data sets. Given that this second approach aims for general results, it must be tested for multiple cities. Examples include a multiplex network study of multimodality (Natera Orozco et al., 2020), methods to prioritize pop-up active transport infrastructure (Lovelace et al., 2020), linking disconnected components (Natera Orozco et al., 2020), or growing bicycle networks from scratch (Szell et al., 2021).

Our approach developed here complements Natera Orozco et al. (2020) and Szell et al. (2021), see Fig. 1: Instead of providing optimized improvements to cities with minimal existing networks (Szell et al., 2021), or to cities with developed but still quite disconnected networks (Natera Orozco et al., 2020), here we focus on repairing networks that are so well developed that their largest connected components already cover the majority of nodes. These networks do not benefit from an approach that starts from scratch. They can benefit from connecting existing components (Natera Orozco et al., 2020), but since they cover already most of the city, this benefit becomes exhausted quickly once the few biggest components have been linked up. However, there can still be many missing links left *within* their connected components, for which we set up an automated fixing procedure here, see Fig. 2. We develop a generalized procedure to find the most important gaps in a bicycle network, and apply it to the city of Copenhagen. Due to the detailed evaluation procedure carried out to demonstrate the applicability of our method, as well as our aim to provide concrete assistance to the Municipality of Copenhagen, we focus on only one use case. However, our procedure should be applicable to other cities without major adjustments.

The IPCC procedure

A cyclist on their way through a well-connected, developed bicycle network like in Copenhagen will often find themselves suddenly having to share the road with cars for a while, or having to cross unprotected intersections with a

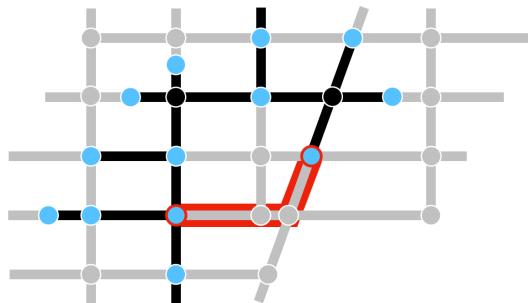


FIGURE 3 Illustration of node and link types, and of our definition of gap. Black links denote protected bicycle infrastructure, grey links a lack of it. Grey nodes are between unprotected links only, black nodes are between protected links only. Blue nodes are “contact nodes” between links of different types. We define a gap as a shortest path between two contact nodes that consists only of unprotected links. An example of a gap between the two highlighted contact nodes is illustrated in red.

high traffic load. Here we formalize this intuitive concept of a “missing link” in the bicycle network and develop an automated procedure to find the most important ones. We call our procedure *IPCC* after its four main steps: Identify, Prioritize, Cluster, Classify, which we present in this section. The IPCC procedure is illustrated in the workflow diagram in Fig. 2, and described in detail in the sections below. This procedure is most applicable to cities that have an already well developed bicycle network such as Copenhagen; see Section *Scope and limitations* for details on the limitations of this approach. We start by outlining the network data structure and our formal definition of “gap” used for the first step of the IPCC procedure, gap identification.

| Gap identification

As a starting point, the IPCC procedure takes an urban network of streets and protected bicycle tracks, as provided by OpenStreetMap (OSM). The steps to obtain and process the data are described in detail in Appendix A. The data are structured as a multiplex network (Battiston *et al.*, 2014) with two different link types and three different node types, see Fig. 3. Links of type “unprotected”, shown in grey, denote street segments that are designed for motor vehicles and lack protected bicycle infrastructure. Links of type “protected”, shown in black, denote protected bicycle infrastructure – either alongside a street segment or off-street. If a node has only one type of links adjacent to it, we call the node either a protected node, shown in black, or an unprotected node, shown in grey. If a node has both protected and unprotected links adjacent to it, we call it a contact node, shown in blue.

We then define a gap as a shortest path between two contact nodes that consists only of unprotected links. This definition is based on the rationale that a gap should be a continuous piece of “missing” protected infrastructure, and it should be as short as possible. An example of a gap following this basic definition is illustrated in red in Fig. 3.

For identifying gaps in our Copenhagen data set, we applied the Dijkstra all-pair shortest path algorithm to the entire street network with links weighted by length. From the set of paths obtained, we discarded all paths that do not meet our gap definition, i.e. the start and end nodes must be contact nodes and all links must be unprotected. In this way, 9924 unique gaps were identified in our Copenhagen data set.

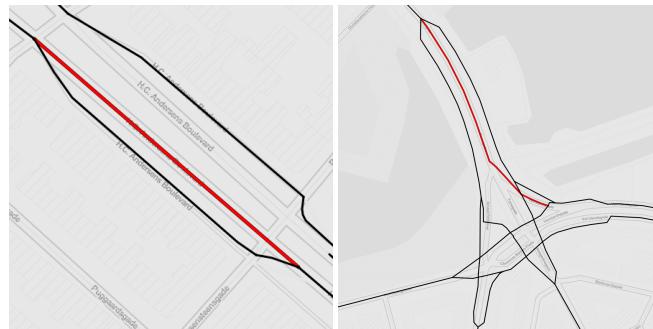


FIGURE 4 Two examples of parallel paths that a gap identification process must account for. The bicycle network is shown in black. The parallel paths along the car network are shown in red; they are only slightly longer and should not be identified as gaps. Left: Parallel path along H.C. Andersens Boulevard. Right: Parallel path along Torvegade.

| Discarding parallel paths

Before proceeding to evaluating the benefits of closing gaps, we must ask whether our working definition of “gaps” will yield a meaningful set of potential “missing links”, or whether we need to refine our approach. Indeed, applying our definition to Copenhagen’s street network reveals the problem of *parallel paths* that needs to be accounted for. This problem comes from the naive application of the shortest path algorithm which does not account for the common occurrence of protected off-street bicycle tracks that run in parallel to car lanes. In these cases, the shortest path algorithm with links weighted by length chooses the slightly shorter car path over the slightly longer bicycle path (see Fig. 4), and therefore undesirably detects a gap located on the car lane despite a protected bicycle track running next to it. The parallel paths problem is a consequence of applying the shortest path algorithm to a relatively high-resolution network layer. However, lowering the resolution is not an option, because using map data with a high resolution of the street segments is necessary for identifying the gaps that we are looking for. This is a well-known problem in transportation network modeling: If a high-resolution layer is given as input, solving a routing problem at a lower resolution is a non-trivial task (Zhu and Chiu, 2015; Perrine et al., 2015).

We therefore applied the following mitigation strategy for parallel paths: For each identified gap g , we first computed the detour factor $D(g) = \frac{d_{\text{prot}}(g)}{d_{\text{all}}(g)}$, where $d_{\text{prot}}(g)$ and $d_{\text{all}}(g)$ are the shortest network path distances on the network of protected bicycle infrastructure and on the entire street network, respectively. We then set a minimum detour value $D_{\min} = 1.5$ and discarded all previously identified gaps that had $D(g) < D_{\min}$.

We arrived at the detour factor value of 1.5 by manually comparing the results of applying a cut-off value for gap rank and the declustering heuristic (see sections *Gap prioritization* and *Gap declustering* below) first to the list of gaps with $D(g) \geq D_{\min}$ and then to the list of gaps with $D(g) < D_{\min}$, for different values of $1 < D_{\min} < 2$. Setting $D_{\min} = 1.5$ yielded the fewest false positives and false negatives. For gaps with a detour factor of $D(g) \geq 1.5$, there were only 10% of false positives, i.e. gaps with a detour factor of over 1.5 that turned out to be parallel paths and had to be excluded manually. For the gaps with a detour factor $D(g) < 1.5$, we found three types of gaps: 1) an expected high percentage of 49% of parallel edges, 2) in 43% of cases a partial overlap with gaps of a higher detour factor and therefore no substantial loss of information when excluded, 3) only 8% of false negatives, i.e. actual gaps on the bicycle network. The chosen detour factor therefore presents a reasonable trade-off between minimizing false positives (roughly 10% of the gaps that had to be excluded manually) and loss of information (roughly 8% of

automatically excluded gaps that were actually relevant).

Excluding gaps with a detour factor below 1.5 from our analysis reduces the number of gaps from 9924 to 6603. This list of 6603 identified gaps is used as input for the next step of the IPCC procedure: gap prioritization.

| Gap prioritization

Not all street segments that were identified so far as gaps are equally suitable for the construction of new bicycle infrastructure, nor are they equally relevant for the overall performance of the bicycle network. Consider and contrast two examples of locations without protected bicycle infrastructure: a residential street in a suburban area, versus a narrow bridge over a canal in the city center. To put a number on the priority of each of these gaps, we need to ask not only “How central is this missing link?” and “How much does it cost to close this gap?”, but also “How many citizens will benefit from closing it?” Therefore, after having found all gaps which fit our topological definition, the next step is to evaluate the benefits of “closing a gap” (by installing protected bicycle infrastructure) for the overall performance of the bicycle network, and to prioritize the list of gaps by this benefit metric.

To quantify the benefit of “closing a gap”, we start off with the rationale that the positive impact consists in reducing the number of meters that cyclists have to ride in the same space as motorized traffic. This is in line with the concept of “planning for the vulnerable”, i.e. aiming to provide an inclusive transportation system by protecting the most vulnerable population groups — such as children, who ideally should never have to cycle in mixed traffic (McDonald, 2012). If this concept was taken to the extreme, no single gap should be left unclosed, which is not a realistic goal. Therefore, we aim to approach this ideal *most effectively* by prioritizing gaps that lie on the most commonly taken bicycle routes. Using topological street network data only, the most common routes can be gauged quantitatively by selecting gaps with the highest link betweenness centrality weighted by gap length. Let us provide an example before the formal definition. Assume that gap A has a length of 10 m and a traffic volume of 50 cyclists in a time unit (e.g. during one hour); and gap B has a length of 20 m and a traffic volume of 15 cyclists. Then, by multiplying lengths with traffic volumes, we obtain the total number of meters cycled in mixed traffic: 500 m for gap A and 300 m for gap B. Closing gap A would avoid more meters cycled in mixed traffic, which is why gap A is ranked more relevant than gap B. In this case gap A is also shorter, therefore also more cost-efficient to close.

In order to apply this rationale, we estimated the number of cyclists on each link, i.e. the bicycle traffic flow through the network, based on the network topology, using betweenness centrality. Betweenness centrality, derived from an all-pair shortest path algorithm, is the most basic proxy for traffic demand. It assumes that for each possible origin-destination combination, there is one “cyclist unit” making their way through the network, always choosing the shortest possible path between origin and destination. Then the number of cyclists that use a specific link on their way through the network, divided by the total number of cyclists on the network, will yield the fraction of cyclists that we expect to find on this link. Thus, the betweenness centrality indicates how “central” or relevant a link is for the flow of cyclists through the whole network. Similar approaches based on betweenness centrality have previously been used to estimate bicycle and motorized traffic flow (McDaniel et al., 2014; Jayasinghe et al., 2015; Ye et al., 2016). This simple model can be refined arbitrarily by replacing betweenness with any other demand model, such as a gravity model, or with empirical flow data, but this refinement is outside the scope of this work.

There is a non-trivial dependence of flow-based centrality metrics on changes in network boundaries. This phenomenon, known as “network edge effect” (Okabe, 2012) or “border effect” (Porta. et al., 2006), also has relevant implications for equity considerations, since centrality metrics like betweenness have an inherent bias towards the center of the network. To account for this network edge effect, we introduced a cut-off radius λ for the set of shortest paths, based on which the centrality metrics are computed (Gil, 2017; Yamaoka et al., 2021). Setting this locality

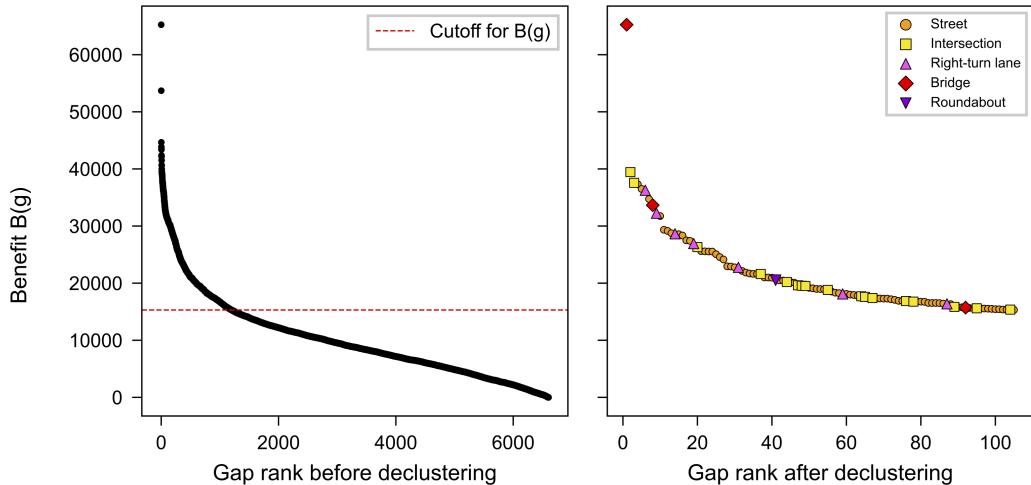


FIGURE 5 Heterogeneity of gap closure benefits. The distribution of the benefit metric $B(g)$ for the Copenhagen gaps before (left) and after (right) prioritization, declustering and error correction. The highest ranked gaps have a much higher benefit for the overall network; bridges tendentially fall into this category. The dashed red line on the left plot shows the benefit cut-off value used in the prioritization step. The colors in the left plot represent different gap classes (see section *Gap classification*).

parameter $\lambda = \infty$ in the shortest path algorithm would consider the entire street network for origin-destination pairs, finding gaps that are most relevant for the whole city and have a tendency to be located more centrally. By contrast, we used $\lambda = 2500$ m to include only destination nodes that are within a maximum path length of 2500 meters from each origin node, finding gaps that are relevant for sub-city scale flows, e.g. on district or neighborhood scales. We chose this particular length as it roughly corresponds to the average diameter of the administrative districts of Copenhagen (Trap Danmark, 2021), and lies in the range of 2–4.9 km, which is the most frequent bicycle trip length range within Copenhagen (Københavns Kommune, Teknik- og Miljøforvaltningen, 2021). By using a finite λ in our calculations, we obtain several benefits: the bias towards the center of the network is decreased; the local importance of the identified gaps can be regulated; and, lastly, computation time is substantially reduced, which is particularly relevant for larger cities.

We applied the locality parameter λ to the set of all shortest paths \mathcal{P} to compute the link betweenness centrality $c_\lambda(I) = \sum_{d(i,j) < \lambda} n_I(i,j)$ for each link I , where $n_I(i,j)$ is the number of times the link I appears in \mathcal{P} . By multiplying the betweenness centrality $c_\lambda(I)$ of link I by its length $L(I)$, we obtained the total number of expected meters cycled on this link, the link closure benefit $B_\lambda^*(I)$. Since a gap g can consist of several links, the gap closure benefit $B_\lambda^*(g)$ is obtained from adding up the link closure benefits of each of the links I :

$$B_\lambda^*(g) = \sum_{I \in g} c_\lambda(I) \cdot L(I) \quad (1)$$

As a last step, we account for cost-efficiency. We assume for simplicity, and in line with previous studies (Mauttone

et al., 2017), that construction costs are generally proportional to facility length. We therefore divide the expected meters cycled $B_\lambda^*(\mathbf{g})$ by the gap's total length $L(\mathbf{g}) = \sum_{l \in \mathbf{g}} L(l)$ and thus obtain the expected meters cycled per investment unit that would be avoided if the gap was closed:

$$B_\lambda(\mathbf{g}) = \frac{B_\lambda^*(\mathbf{g})}{L(\mathbf{g})} \quad (2)$$

This model is extendable with further weights, for example with data on specific road hazards or stress levels (Furth et al., 2016; Chen et al., 2017), or by a non-linear cost function. However, for sake of simplicity and generality, we do not assign any further weights here. This corresponds to the simplifying assumption that for each cyclist, every meter cycled jointly with motorized traffic equally contributes to the risk of getting injured or killed. Note that for the case of gaps that consist of only one link, eq. (2) simplifies to $B_\lambda(\mathbf{g}) = c_\lambda(l)$ since the two expressions for total gap length cancel out. From here onwards, we drop the index λ for simplicity and denote the gap closure benefit as $B(\mathbf{g})$.

The benefit metric $B(\mathbf{g})$ will be used for gap prioritization. To summarize, it expresses the benefits of closing a gap \mathbf{g} in terms of number of expected meters cycled in mixed traffic per unit of investment. Fig. 5 (left) shows the distribution of $B(\mathbf{g})$ for Copenhagen within the list of 6603 gaps that were found with a minimum detour of $D_{\min} \geq 1.5$. This distribution shows a large heterogeneity of benefits due to the heavy-tailed distribution of betweenness in street networks (Kirkley et al., 2018). In other words, there is a small subset of highest-ranked gaps which account for a substantial amount of the total benefit. After inspecting the heterogeneity of benefits, Fig. 5 (left), we chose a cut-off at $B(\mathbf{g}) \geq 15\,000$ where the growth of the rank-ordered benefits changes qualitatively, thereby selecting approximately the highest ranked 20% of gaps. This selection provides an ordered list of the 1199 highest-ranked gaps which is used as input to the next step of our IPCC procedure: gap clustering.

| Gap clustering

In many cases, two or more prioritized gaps partially overlap, forming a *gap cluster* that is not a simple path anymore. An example of gap clustering in Copenhagen is shown in Fig. 6 (left): Because the intersection of C.F. Richs Vej and Grøndals Parkvej is represented by several network nodes, all shortest paths to destination node D from any of the origin nodes A, B, C are classified as gaps and display similar benefit values $B(\mathbf{g})$. This gap cluster example illustrates that it is not always meaningful to provide all street segments that constitute a gap cluster with protected bicycle infrastructure. The appearance of gap clusters in the results can also be understood by recalling our gap-finding procedure and network characteristics: First, all network are considered as equally likely origins or destinations; second, gaps consist of car links and start and end on a contact node; and third, the network is characterized by a high node density e.g. at intersections of streets with multiple lanes. Taken together, these three points help explain that gaps will often consist of a combination of high and low centrality links, and moreover, gaps will often partially overlap, meaning that the same street segment will appear in several gaps – for example, the network link on Brønshøjvej appears in more than 100 of the 6603 gaps found.

The urban planning task of identifying the exact subnetworks within these gap clusters for the construction of infrastructure to “close the gap” is beyond the scope of the present study. However, we developed a declustering heuristic, described in detail in Appendix A, which is a first approach to break down a gap cluster into separate components that are simple paths, based on the same benefit metric derived $B(\mathbf{g})$ from betweenness centrality. See Fig. 6 (right) for a non-trivial gap cluster with links colored by edge betweenness centrality values and the resulting declustered gaps. After applying the gap declustering heuristic, using the list of 1199 highest-ranked gaps as input, we obtain a list of 134 gaps. This list is used as input for the next step of the IPCC procedure: gap classification.



FIGURE 6 Example of gap clusters, and of the declustering heuristic. Left: Shown in red, on C.F. Richs Vej. The three gaps AD, BD and CD overlap and have similar closure benefits $B(g)$. Therefore, the three gaps are merged into one gap cluster to be handled jointly. Right: A declustering heuristic can help deciding which parts to retain and which ones to discard. The links of the shown gap cluster are colored by betweenness centrality; darker tones represent higher values. The black borders indicate the declustered gaps after one and two runs of the heuristic.

| Gap classification

The last step in the IPCC procedure is the classification of gaps. The gap classification scheme described in this section was developed through manual inspection and on-site visits of the gaps identified in Copenhagen, hence it might need to be adapted or extended for other urban contexts in future research. We identified the following gap classes: Street (ST); intersection (IS); right-turn lane (RT); bridge (BR); roundabout (RA); and error (ER). This classification scheme is meant to facilitate both the interpretation of results from bicycle network analysis and the decision-making within a subsequent planning process. In this section, we describe the general concept behind each of the gap classes before discussing the specific results for Copenhagen.

Street

The gap class *street* corresponds most intuitively to the idea of a “gap in the bicycle network”, i.e. a generic street segment without protected bicycle infrastructure. We define as street gap all mixed-traffic street segments whose both ends connect to protected bicycle infrastructure and that do not correspond to any of the other gap classes (bridge, intersection, roundabout, right-turn lane, or error).

Intersection

Missing links without protected bicycle infrastructure found at crossings of two or more streets are classified as *intersection*. Given that a high proportion of traffic crashes occur at intersections, intersection design is crucial for cyclist safety (Thomas and DeRobertis, 2013). By the very nature of an intersection, a potential for conflict between traffic participants cannot be brought to zero; however, it can be minimized with appropriate planning (de Groot, 2016). Intersection design deserves to be considered a discipline of its own right, and different network analysis methods than the one used in this study might need to be applied to explicitly identify problematic intersections from a bicycle network planning perspective (Furth et al., 2016).

In the present study, we do not model intersections separately, but rather identify them as gap class in the last step of the procedure. Due to the underlying data structure in OSM, intersections could only be identified as gaps

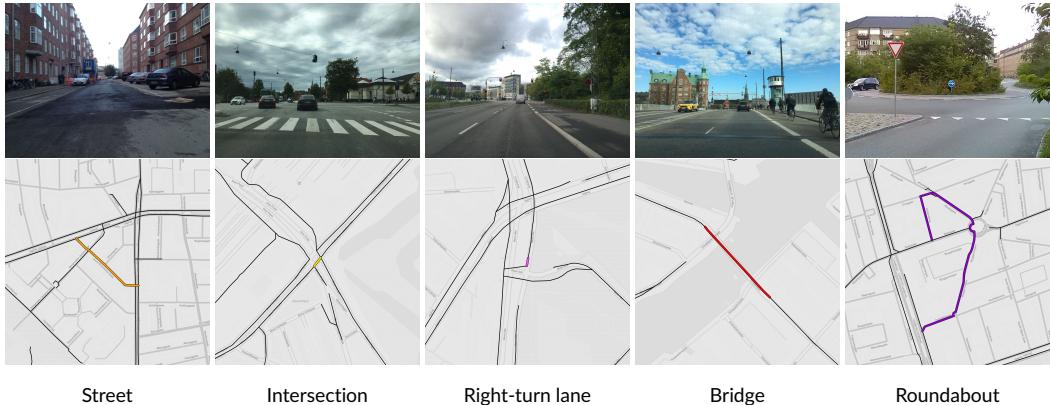


FIGURE 7 The five gap classes in Copenhagen. For each class, the highest ranked gap is shown. From left to right: Street gap (rank 4) on Jacob Erlandsens Gade; Intersection gap (rank 2) at the intersection of Øster Voldgade and Grønningen; Right-turn lane gap (rank 6) at the right-turn from Nørre Allé to Øster Allé; Bridge gap (rank 1) on Knippelsbro; Roundabout gap (rank 41) at Sankt Kjelds Plads.

within the IPCC procedure if they contained at least one link, rather than just nodes. Additionally, there is a lack of consistency in OSM tagging when it comes to the designation of specific intersection segments as “protected” or “unprotected”. The caveats of this approach are addressed in more detail in Section *Scope and limitations* and in Appendix A.

Right-turn lane

We classify intersection approaches where the lane for right-turning cars merges with the adjacent cycle lane as *right-turn lane* gaps. In such cases, the bicycle path ceases to be part of the protected bicycle network as it approaches an intersection, and cyclists are forced to mix with motorized traffic – see Fig. 7 for an example. This type of intersection approach design is a common feature of Copenhagen’s bicycle network (Vejdirektoratet, 2017). The Danish Road Directorate argues in favour of an intersection approach design with shortened cycle tracks where cyclists and cars mix for right turns (Sørensen et al., 2020; Vejdirektoratet, 2020), while international best practice standards recommend intersections that protect and prioritize cyclists (Wagenbuur, 2014; de Groot, 2016; National Association of City Transportation Officials (NACTO), 2019), such as dedicated bicycle queue areas and corner wedges or islands. Here we adhere to the international standards and to the rationale of demanding continuity for the network of protected bicycle infrastructure.

Bridge

We classify missing links on obstacle-crossing road segments as *bridge* gaps. In locations where there are physical barriers such as water bodies or railway tracks that have to be crossed, bridges play a particularly important function for connecting parts of the network and often constitute bottlenecks for traffic flow. At the same time, there are often inherent constraints to placing additional infrastructural elements on bridges due to limited physical space available (Wang et al., 2019).

Color	Acronym	Gap type	Count	Average benefit $\langle B \rangle_g$
Orange	ST	Street	77	20 544
Yellow	IS	Intersection	17	20 925
Magenta	RT	Right-turn lane	7	25 911
Red	BR	Bridge	3	38 207
Purple	RA	Roundabout	1	20 518

TABLE 1 Distribution of gap classes for the top 105 gaps in Copenhagen. Bridges are most important.

Roundabout

Since requirements for roundabout design are not the same as for intersections, we separately define the gap class *roundabout*. Roundabouts are often considered to be the safer option for cyclists (Dufour, 2010; Jensen, 2017; U.S. Department of Transportation, Federal Highway Administration, 2017), depending on traffic volume (de Groot, 2016). A roundabout with more than one lane puts cyclists at danger (Dufour, 2010). According to a recent literature review by Poudel and Singleton (2021), data from Northern Europe suggests that the number of bicycle crashes might actually be higher for roundabouts than for intersections. There are several roundabout design options focusing on cyclist safety (Sakshaug *et al.*, 2010), such as the Zwolle roundabout, named after the Dutch city that first introduced it (de Groot, 2016; Wagenbuur, 2013).

Error

We classify gaps that have been identified by the IPCC procedure, but were not confirmed as such via visual inspection, as *errors*. There are two types of errors: *parallel paths* and *data issues*. Parallel paths, as described in section *Discarding parallel paths* above, are errors stemming from the routing problem in high resolution networks. Data issues are errors due to incorrect information on OSM. There are many possible reasons for errors in the OSM data: segments might be missing, mistagged, or outdated. The implications of OSM data quality on the results of this study are discussed in detail in section *Scope and limitations*.

Finding gaps in Copenhagen with IPCC: The top 105 gaps

In this section, we discuss the results of the IPCC procedure applied to the use case of Copenhagen. From the list of 134 gaps that were used as input for the last classification step of the IPCC procedure, we discarded 29 gaps classified as errors. We confirmed and classified the remaining gaps through manual inspection and on-site visits and obtained a list of 105 top priority gaps, which is the final result of the IPCC procedure applied to Copenhagen. The distribution of gap classes in the top 105 gaps is reported in Table 1 (class *error* excluded). The map in Fig. 8 gives an overview of all 105 gaps, with classes plotted by color. In the next sections, we summarize the results per gap class. A list of all 105 confirmed gaps with detail maps and addresses can be found in Appendix C.

Streets

Gaps classified as *street* constitute the majority of our final result (77 out of 105 gaps). Both visual analysis of the gap location and a comparison with Copenhagen's current Cycle Path Prioritization Plan (see section *Comparison with Copenhagen's Cycle Path Prioritization Plan* below) indicate that several of the identified street gaps might be confirmed as relevant by transport planning practitioners; for example, gap 5 on Tåsingegade (see Fig. 9), Gap 17 on Ålandsgade

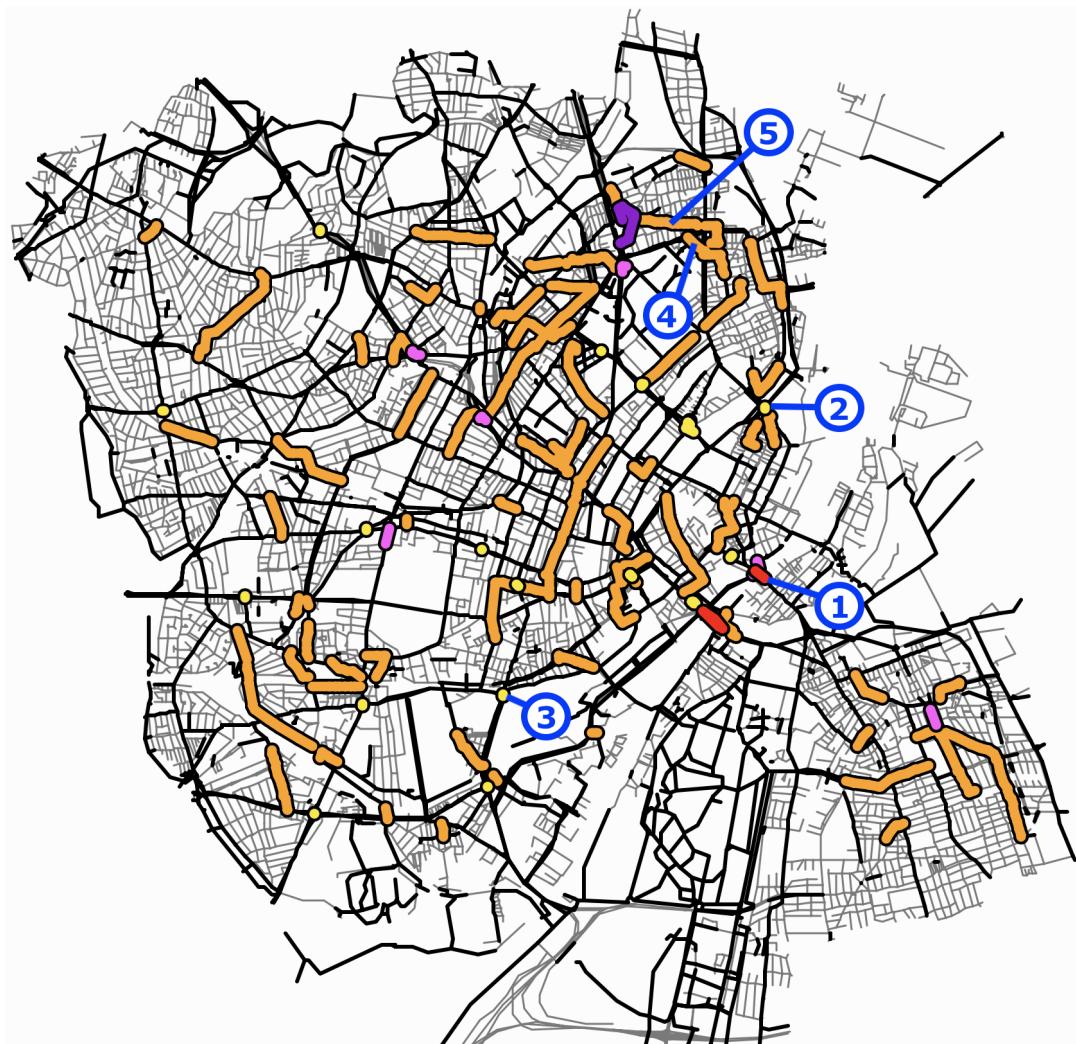


FIGURE 8 Overview map of top 105 gaps by class: streets in orange, intersections in yellow, bridges in red, right-turn lanes in pink, roundabouts in violet. Errors are not shown. Numbered blue circles indicate the top 5 gaps (see Fig. 9 for detail plots). The street network is shown in grey, the bicycle network in black. See <http://fixbike.net> for an interactive version.



FIGURE 9 Detail plots of the top 5 gaps in Copenhagen. From left to right: Gap 1: Knippelsbro (bridge); Gap 2: Øster Voldgade and Sølvgade (intersection); Gap 3: Enghavevej and Vigerslev Allé (intersection); Gap 4: Jacob Erlandsens gade (street); Gap 5: Tåsingegade (street).

and Frankrigshusene, or gap 23 on Hamletsgade (see Appendix C). Some of the identified street gaps are found on residential streets with presumably low traffic speed and volume, so they would probably not be prioritized from a transport planning perspective in spite of their estimated local relevance indicated by high betweenness values. For example, gap 4 on Jacob Erlandsens Gade (see Fig. 7) shows that this short street – although low-traffic – is an important structural shortcut between the many paths connecting east of Østerbrogade and north of Jagtvej. For a refinement of the procedure, a further distinction of subcategories within the street gap class, both by road conditions (e.g. speed limit) and by empirical traffic volume data, if available, would be recommended, as it might help to estimate whether these links can be considered safely bikeable in spite of their lack of designated infrastructure (de Groot, 2016).

Several street gaps come to lie within a locally sparse area of the network and are identified by the IPCC procedure due to the presence of small, isolated bicycle infrastructure elements in their vicinity. Examples are gap 46 on Valløej and gap 62 on Oxford Allé (see Appendix C). This is a direct consequence of our initial definition of a gap as a path between two bicycle infrastructure elements; hence, in network areas where no bicycle infrastructure at all is present, no gap will be identified, which makes the IPCC procedure less suitable for sparse network areas.

Intersections

With 17 out of the top 105 gaps, intersections are the second most common gap class. As outlined in the section on gap classification, due to both the data structure and data quality issues in OSM, the IPCC list of gaps classified as *intersection* should be understood as a non-exhaustive list of locations where checking for appropriate intersection design is recommended. It is noteworthy that most of the intersections identified by the IPCC procedure also received a considerable number of mentions as “busy intersections” in the citizen survey within the Cycle Plan. This is seen, for example, for gap 2 at Øster Voldgade and Grønningen and gap 3 at Enghave Vej and Vigerslev Allé (see Fig. 9), as well as gap 65 at H.C. Andersens Boulevard and Rystensteensgade (see Appendix C).

Right-turn lanes

Seven out of the top 105 maps are classified as *right-turn lane*. Examples are gap 6 at Nørre Allé and Øster Allé (see Fig. 7), gap 9 at Backersvej and Øresundsvej and gap 14 at Borups Allé and Hillerødsgade (see Appendix C). The relatively low number of right-turn lanes in the top 105 gaps identified by the IPCC procedure can partially be explained by tagging inconsistency in OSM, already mentioned above with regard to intersections. We deem it likely that there is a significant number of false negatives, i.e. right-turns that have not been identified as gaps by the IPCC procedure because they are tagged as “protected bicycle track” in OSM. Investigating both the OSM data quality and the objective

and subjective safety implications of intersection approach design call for further research.

Bridges

There are 3 gaps classified as *bridge* within the top 105 gaps: gap 1 on Knippelsbro (see Fig. 7) and gaps 8 and 92 on Langebro (see Appendix C). We have already argued for the physical separation of cyclists from motorized vehicles; it is of even higher relevance for the crossing of bridges (Melson et al., 2014). In the case of Copenhagen, bridges play a particularly relevant role as the city is situated on the two islands of Amager and Zealand, and harbours an extensive canal system. According to Copenhagen's latest Bicycle Account, 7 of the top 10 most heavily trafficked cycling stretches in the city are bridges (City of Copenhagen, Technical and Environmental Administration, 2019). The first three stretches on that list are Dronning Louises Bro, Langebro and Knippelsbro. While Dronning Louises Bro is provided with protected bicycle infrastructure, Langebro and Knippelsbro are not. This aligns well with the results of the IPCC procedure, given that both Langebro and Knippelsbro are listed within the top 105 gaps. The Municipality of Copenhagen is currently in the process of upgrading the cycle lanes on both these bridges to cycle tracks (Københavns Kommune, Teknik- og Miljøforvaltningen, 2017). The average benefit of closing a gap classified as *bridge* is almost twice as high as the average benefit for all other gap classes, see table 1. This insight is in line with the underlying network topology – such “bridge edges” in infrastructure networks are important connections between otherwise separated or even disconnected parts of the network and therefore have particularly high betweenness centrality values.

Roundabouts

The only gap from the list of top 105 gaps classified as *roundabout* is gap 41 on Australiensvej/Bryggerivangen and Sankt Kjelds Plads. The gap contains two roundabouts: the bigger one, on Sankt Kjelds Plads, and the smaller one on the intersection of Australiensvej and Bryggervangen. The Sankt Kjelds Plads roundabout consists of only one lane where motorized vehicles and bicycles mix (see Fig. 7). Same as in the case of intersections, future work might consider the set of all roundabouts in the city of Copenhagen and examine their design from a cyclist safety perspective.

Errors

Out of the 29 gaps that have been discarded as errors within the last step of the IPCC procedure, classification, 15 were parallel paths (discussed in detail in section *Discarding parallel paths*) and 14 were data issues in OSM. Overview plots of all errors are found in Appendix B. Many of the parallel paths occur at large intersections or along streets with multiple lanes and bicycle infrastructure on both sides, for example, at Lyngbyvej or at the crossing of Frederikssundsvej and Borups Allé. Several parallel paths coincide with some of the busiest bicycle corridors in the city, such as Dybbølsbro and H.C. Andersens Boulevard, which is an encouraging observation for the use of betweenness centrality as a proxy for bicycle traffic flow. All data issues were due to missing tags for protected bicycle infrastructure in OSM, leading to the IPCC procedure identifying gaps in locations where protected bicycle infrastructure is already in place. While some of the missing OSM tags correspond to relatively recent construction of infrastructure, others contain infrastructure that dates back more than a decade.

| Comparison with Copenhagen's Cycle Path Prioritization Plan

The Municipality of Copenhagen's Technical and Environmental Administration (*Teknik- og Miljøforvaltningen*) regularly publishes a Cycle Path Prioritization Plan (*Cykelstiprioriteringsplan*, hereafter referred to as Cycle Plan). The current plan for the period 2017–2025 (Københavns Kommune, Teknik- og Miljøforvaltningen, 2017) contains an overview



FIGURE 10 Overview map of citizen survey data. Citizen responses on missing bicycle tracks and busy intersections are represented by blue dots. The street network is shown in grey, the bicycle network in black.

of planned infrastructure improvements and measures targeted at increasing the modal share of cycling, split into five categories: new bicycle infrastructure (tracks, lanes, sharrows), improved intersection design, improvements of the Super Cycle Paths (*Supercykelstier*) network, improvements of the Green Cycle Routes (*Grønne cykelruter*) network, and finally, widening of existing cycle tracks. We conducted a comparative analysis of our list of top 105 prioritized gaps with the planned infrastructure improvements listed in the Cycle Plan across all categories except the last one (given that the width of bicycle infrastructure was not considered in this study). The comparison shows a considerable overlap, given that 46 out of 105 gaps identified by the IPCC procedure are found in locations that are also prioritized in the Cycle Plan. There is a particularly good overlap with the list of high priority routes for new cycle tracks (*højt prioriterede strækninger til nye cykelstier*): 19 out of 35 prioritized routes are included in our list of top 105 prioritized gaps (Københavns Kommune, Teknik- og Miljøforvaltningen, 2017, p. 17). Further categories that show considerable overlap are the list of cycle lanes to be upgraded to cycle tracks (coinciding with 11 of our gaps); as well as identified missing links and planned upgrades of the Green Cycle Routes network (coinciding with 10 of our gaps).

The Cycle Plan also contains the results from a citizen survey on bicycle infrastructure improvements, conducted by the Municipality of Copenhagen in September and October 2016 (Københavns Kommune, Teknik- og Miljøfor-

valtningen, 2017), which we used for a further qualitative assessment of the present study. Results from the citizen survey consist of a set of geocoded locations, indicated by respondents through clicking on a digital map, for each of the following categories: *Cykelsti mangler* (cycle track missing), *Cykelsti for smal* (cycle track too narrow) and *Kryds med stor traengsel* (busy intersection). We did not utilize responses from the category on too narrow cycle tracks, given that street width was not accounted for in the present study. Figure 10 provides an overview of the processed data from the citizen survey.

A qualitative comparison of our list of top 105 prioritized gaps with the citizen survey results shows considerable overlaps at several locations. Examples are shown in Fig. 11. In total, 71 out of our 105 gaps have at least one mention in the considered categories of the citizen survey. Although these overlaps are encouraging at first glance, there is a relevant caveat to consider. While participatory approaches can improve the equity impact of transportation plans (Boisjoly and Yengoh, 2017), a failure to adequately design them might introduce biases and undermine the applicability of the findings (Schonlau *et al.*, 2009; Nohr and Liew, 2018). A reliable survey design should account for several bias/equity considerations, such as survey language, medium used, distribution channels and socio-demographic variables of respondents. We have no information about such considerations (or the lack thereof) for the survey data at hand. Therefore, if a location has no mentions in the citizen survey, it cannot be concluded that the infrastructure is already satisfactory there – it might be due to an undersampling of residents from that area. As long as such considerations in the citizen survey design are unclear, its results should not be regarded as reliable ground truth.

The partial overlap of our top 105 gaps with the locations prioritized by the Municipality of Copenhagen in the Cycle Plan, as well as with the citizen survey results, is a first proof of concept for the IPCC procedure. At the same time, the gaps from our results that do not show up in the Cycle Plan are of particular interest for further evaluation, enhancement of methods and decision-making. In a future dialogue with the Municipality of Copenhagen, the results from the IPCC procedure could be scrutinized to find out which gaps are actual missing links in the bicycle network of Copenhagen and possibly will be prioritized in future infrastructure investments; which gaps are less relevant from an urban planning perspective and indicate a necessity to adjust our method (e.g. by adding information on street type or non-protected bicycle infrastructure to the analysis); and finally, which gaps have been wrongly identified due to data issues in OpenStreetMap. Thus, the comparison with Copenhagen's Cycle Plan demonstrate that the IPCC procedure has the potential to be used as automated assistance tool and to successfully complement manual planning processes, while its results can and must be further scrutinized by urban planners.

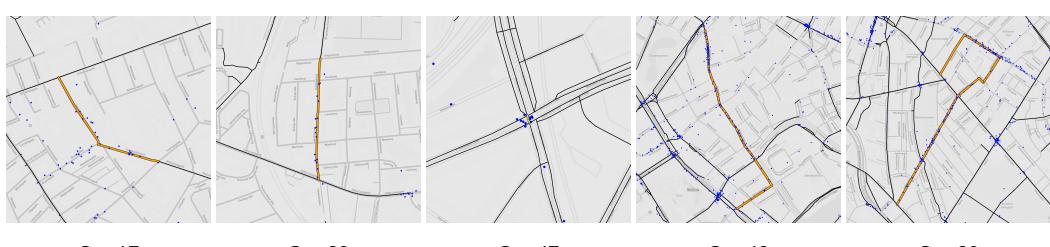


FIGURE 11 Five examples of overlaps between gaps found by the IPCC procedure and citizen survey results (blue dots). From left to right: Gap 17 on Ålandsgade and Frankrigshusene; Gap 30 on Gåsebæksvej; Gap 47 on the intersection of Enghavevej with P. Knudsens Gade; Gap 69 on Nørregade/Rådhusstræde/Ny Kongensgade; Gap 90 on Stefansgade/Gormsgade/Mimersgade.

Discussion

Our results from the Copenhagen case study suggest that benefits from bicycle infrastructure improvements for overall network quality are highly variable and location-dependent, with the gap class *bridge* showing the highest average benefits. We also find that network edge effects in transport network analysis might have detrimental implications for the population in the urban periphery, and that future work is needed to mitigate this bias. These findings illustrate the advantages of considering the network as a whole in the analysis, operating on the “macro level”. In practice, bicycle infrastructure planning often is highly localized and guided by manual decision-making, taking place on a “micro level”. Our results show that these two approaches should not be seen in competition, but rather as complementary to each other. This is illustrated by the application of the IPCC procedure to bicycle network of Copenhagen and the comparison of the findings with the city’s Cycle Path Prioritization Plan, since potentially relevant results were obtained in spite of minimum data requirements. We are therefore optimistic about the potential of a computational, data-driven macro level approach to decision-making support for bicycle network planning. The IPCC procedure presented in this study is, however, just a first step towards this goal; in the following sections, we discuss the scope and limitations of our approach, as well as further work needed.

| Scope and limitations

The potentially most substantial limitation for the results of this study is data quality in OpenStreetMap. OSM data is crowdsourced, which allows for the integration of local knowledge and the provision of open source data, but at the same time often leads to data quality issues due to different skill levels within the mapping community and a lack of coherence in tag criteria applications (Kaur and Singh, 2018). In addition, OSM data quality significantly varies by location (Mooney et al., 2010; Haklay, 2010). A broader quantitative assessment of OSM data quality is still an open research question (Yeboah et al., 2021; Jacobs and Mitchell, 2020), particularly for bicycle infrastructure (Ferster et al., 2020). In our results from the IPCC procedure, many of the identified gaps which were discarded as data issues were due to outdated OSM tags, with substantial portions of recently built bicycle infrastructure not yet included in the OSM data. While the number of tagging edits might potentially be used as a workaround for estimating whether the tag is up-to-date (Line, 2021), ideally the implementation of new bicycle infrastructure elements would go hand in hand with the corresponding update in OSM. Another issue is the lack of coherence in bicycle infrastructure tagging. For example, right-turn lanes where the bicycle track merges with a car lane are sometimes marked as protected bicycle infrastructure; the same goes for unprotected intersections which separate two stretches of protected bicycle infrastructure. Therefore, the definitions of bicycle infrastructure categories within OSM (OpenStreetMap Contributors, 2021) might be scrutinized from the viewpoint of intelligibility in order to enhance correct and coherent identification of bicycle infrastructure by mappers across differing local contexts (Ferster et al., 2020).

A further limitation consists in our simplified conceptualization of street and bicycle networks based on protected bicycle infrastructure availability. Our study considers only protected bicycle infrastructure as part of the bicycle network, but unprotected bicycle infrastructure can also be an adequate design solution under certain conditions (de Groot, 2016). By binarizing street categories into “protected” and “unprotected”, we assume that it is equally undesirable to cycle on any of the car-only streets, whereas in reality the propensity to cycle in mixed traffic highly depends on such factors as road type, traffic flow, and number of lanes. While the IPCC procedure for Copenhagen delivered relevant findings in spite of these simplifications, results could be further scrutinized by enhancing the network model through a more fine-grained differentiation of road and bicycle infrastructure types. The level of detail that can be introduced into the network model will depend on the level of data availability.

Similarly, both the calculation of the benefit and the estimation of bicycle traffic flow within the IPCC procedure could be enhanced in case corresponding data is available. In this study, we assumed minimum data availability and estimated traffic flows and construction costs based only on topological network properties. This assumption was followed intentionally, since our aim was to develop a general method. However, if empirical traffic flow measurements, origin-destination tables, census data etc. are available (Olmos *et al.*, 2020), the calculation of a flow centrality, construction costs and total benefit for each network element could be made more accurate. A related caveat in relation to betweenness centrality is the finite λ parameter that we introduced, as a first attempt to partially mitigate the bias towards the network center. The equity implications of centrality metrics have only recently started to be discussed and there is a knowledge gap regarding their quantification (Jafino *et al.*, 2020; Jafino, 2021; Yamaoka *et al.*, 2021). A systematic analysis of such network edge effects would therefore be of high relevance. However, it also goes beyond the scope of the present study, so future work in that regard is urgently called for.

A further simplification is the assumption that cyclists always choose the shortest path from A to B. This is implied in our definition of betweenness centrality, since the shortest path computations on the network are performed with link weight set equal to link length. Several previous studies have accounted for cyclist preferences in shortest paths computations by providing links with a weighting factor that is based on additional features which quantify link attractiveness for cyclists (Broach *et al.*, 2012; Furth *et al.*, 2016; Cervero *et al.*, 2019; Boisjoly *et al.*, 2020). While such an approach may result in more realistic cyclist flow estimations and mitigates the parallel paths problem for some locations on the network, it comes at a considerable cost: A feature-based weighting factor for network links is highly context-dependent, based on potentially subjective cyclist preferences, and constitutes an additional parameter with a non-trivial impact on the shortest path calculations. We therefore explicitly decided not to consider link weighting factors other than link length for our shortest path computations, but extending our model in this respect would be straightforward.

Lastly, given that the classification scheme presented in this study was derived from a qualitative analysis of results for Copenhagen, it might need to be modified for other local contexts. The same goes for the parameters D_{\min} (minimum detour) and $B(g)$ (cut-off benefit) which have been selected for Copenhagen. Appropriate values for both parameters have been derived empirically, but no statement can be made concerning appropriate parameter values for other cities. Although these two thresholds were selected manually, we do not expect this to affect the robustness of our results – rather, we expect an adjustment of thresholds to mostly impact the number of gaps found.

| Future research

Based on the findings from this study, we anticipate four major lines of future research. First, the IPCC procedure presented here should be further improved. As discussed in the previous section, *Scope and limitations*, there are numerous ways to make the IPCC procedure more accurate, including a testing of its applicability to other locations. Second, we call for the urgent development of a solid computational basis for data-driven bicycle network planning, following recent first steps (Olmos *et al.*, 2020; Natera Orozco *et al.*, 2020; Mahfouz *et al.*, 2021). We deem it particularly relevant to consider multimodality and the multiplex transport network of a city as a whole (Natera Orozco *et al.*, 2021), and to include equity considerations as an integral part of the network analysis process (Gössling, 2016; Pereira *et al.*, 2017; Jafino, 2021). Third, we emphasize the importance of bicycle infrastructure data quality, availability, and coherence (Ferster *et al.*, 2020). Access to high quality data is a necessary precondition to provide a scientific basis for any substantial systemic shift towards more active mobility. Fourth and lastly, in line with our call for better cycling data and for data-driven planning approaches, we recommend to account for limited data availability and corresponding mitigation options in any future work on bicycle network planning.

Conclusion

In this study, we developed the IPCC procedure for identifying, prioritizing, clustering and classifying gaps in developed urban bicycle networks. Our method is based only on topological network properties and thus has minimal data requirements. We applied the IPCC procedure to the city of Copenhagen and obtained a list of 105 top priority gaps. A comparison of our results with the city's most recent Cycle Path Prioritization Plan showed substantial overlaps, both with citizen input on missing bicycle network links and with the city's list of prioritized locations for the construction of new bicycle infrastructure. The IPCC procedure demonstrates how data-driven network analysis on a city-wide scale can meaningfully complement manual planning processes. We therefore consider this study a further crucial step towards a consolidation of computational methods for bicycle network analysis.

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Data and code availability

The code for the IPCC procedure, as well as the OSM data used as input for the Copenhagen case study, is available on GitHub: <https://github.com/anastassiavybornova/bikenwgaps>.

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Appendix A: Data Acquisition and Processing

We describe the details of data acquisition and processing, as carried out in the present study, within the following subsections: Data source and data structure; Simplification of OSM data; Representation of intersections in OSM data; and lastly, Declustering. All code described in this section is available on GitHub: <https://github.com/anastassiavybornova/bikenwgaps>.

Data source and data structure

For data acquisition and data processing we used Python and OSMnx (Boeing, 2017). The main data source is OpenStreetMap. The input for the case study on Copenhagen consists of GIS vector data of geographic objects which together form the street network of Copenhagen (streets and intersections, bridges, roundabouts, parking lots, paths through green areas etc.) Intersections are represented as points with geographic coordinates, and street segments are represented as sequences of points. In our network derived from the data, intersections of street segments are interpreted as network nodes, and street segments are interpreted as links.

All input data was downloaded from OSM in February 2021 in csv file format. Data sets were acquired separately for two partially overlapping networks, which, when combined, form the street network of the municipalities of Copenhagen and Frederiksberg: the network of car infrastructure and the network of protected bicycle infrastructure, or, in more simple terms, the car network and the bicycle network. The limits of the two networks coincide with municipality boundaries, which introduces a cut into the continuous fabric of the street network of the Greater Copenhagen area (see the discussion on network edge effects in the section *Gap prioritization*). For each of the two networks, two data sets were generated through OSMnx: one for the nodes and one for the links. Each node from the data set has the attributes geocoordinates and OSM ID; each link has the attributes geocoordinates, OSM ID, length, street name and oneway/toway indication, as well as several attributes which have not been used within the scope of this study, such as type of highway and speed limit.

The data on car and bicycle nodes was combined into one data set and the parameter “node type” was added. Nodes that appeared only in the bicycle data set were assigned the type “protected” and nodes that appeared only in the car data set were assigned the type “unprotected”. Nodes that appeared in both data sets were assigned the type “contact”. After this, duplicates were removed. The same procedure was applied to the car and bicycle link data sets: they were merged into one data set with the “link type” parameter set to “unprotected” (if the link appeared only in the car data set) or to “protected” (if the link appeared in the bicycle data set or in both data sets). Duplicated links, i.e. links with same length and type but opposite origin/destination nodes, were removed.

A graph object was created from the resulting data set using the Python’s networkx library. The resulting network had 77 disconnected components, out of which only the largest connected component was kept, while all other disconnected components were dismissed as negligible for the sake of simplicity. In the real street network of the city, disconnected components, i.e. street segments that are not accessible from any other street segment, are quite rare. The appearance of disconnected components in our data set is mostly due to data quality issues, e.g. missing street segments that should have been classified as protected links.

Simplification of OSM data

Within OSM data, prior to further processing, a curved street is represented by a sequence of several points in geo-coordinates, which are connected by straight lines. We shall call the corresponding degree-two nodes, which are introduced only for the sake of preserving the physical shape of a link, “auxiliary”. The presence of auxiliary nodes in the data set strongly biases the degree distribution of the network towards $d = 2$. The network can be simplified

by replacing a sequence of straight links and their corresponding auxiliary nodes by a single polygon link, while preserving the data on length and coordinates of the aggregated links. OSMnx has a built-in function to export already simplified data sets. For our purposes, however, the simplification had to be carried out on the combined network of protected and unprotected links (as opposed to separately simplifying the car and bicycle network, which is an already automated functionality in OSMnx). This is because nodes which are auxiliary in only one of the two networks would otherwise disappear from the data set, and information on connections and partial overlaps between the car and bicycle networks would be lost in case of separate simplification. Therefore, a network was created from the merged data set of protected/unprotected links and protected/unprotected/contact nodes. Then, a simplification algorithm, described in Box 1, was applied to the network to remove all auxiliary nodes.

For the data set used in the present study, the simplification algorithm terminates after seven runs; the highest number of auxiliary nodes associated with a link in the final, simplified network is 54. The only degree-two nodes that appear in the data set after simplification are either meeting points of two links of different types or nodes that are kept to represent loops on the network while maintaining the network simple, i.e. without parallel links. As expected, the degree distribution of the simplified network significantly differs from the original one, shifting from a high to a low percentage of degree-two nodes.

The final outcome of the data preprocessing is the car and bicycle network of Copenhagen, represented by a simple, loop-free, undirected graph with no auxiliary nodes, where each link has two attributes: *type* ("protected" or "unprotected") and *length*, and each node has the attribute *type* ("protected", "unprotected", or "contact").

```

Input: Network  $H$  with auxiliary nodes
Output: Network  $H'$  without auxiliary nodes

while auxiliary nodes in  $H$  do
    for node in  $H$  do
        if node degree  $d(n) = 2$  and links incident on node have the same type then
            | place node in stack
        end
    end
    while stack is not empty do
        take random node  $n$  from stack;
        if neighbours of  $n$  are neighbours themselves then
            | remove node  $n$  from stack;
        else
            | remove two links incident on node  $n$  from link set of network  $H$ ;
            | add new link connecting two neighbours of  $n$  to the link set of network  $H$ ;
            | set length attribute of new link to sum of lengths of removed links;
            | add geocoordinates of removed links to geocoordinate attribute of new link;
            | remove node  $n$  from node set of network  $H$ ;
            | remove node  $n$  and, if applicable, its two neighbours from stack;
        end
    end
end
```

Box 1: Algorithm for removal of auxiliary nodes from the OSM data set

Representation of intersections in OSM data

Within the OSM data structure, intersections of smaller spatial extent appear as single nodes (a node representing the crossing of two streets), while larger ones appear as a set of nodes and links (each node representing the intersect of two or more lanes – see the example in Fig. 6 where nodes A, B and C are all part of the same intersection). As a rule, but not exclusively, this is the case when at least one of the intersecting streets is bidirectional. Keeping this representation of larger intersections within the data structure allows for the identification of unprotected crossings, that lie on an otherwise protected bicycle track, as gaps in the bicycle network. However, this method of identifying unprotected crossings is by far not exhaustive. This has several reasons. First, due to the data structure, the IPCC procedure does not recognize unprotected intersections that are represented by single nodes in the network model as gaps. Second, even with a clearly outlined set of intersection design criteria at hand which would enable us to discard protected intersections from the gap list, the incoherence of intersection tagging in OSM results in numerous false negatives and false positives: intersections with a protected crossing for cyclists are often tagged as unprotected bicycle infrastructure; intersections without any bicycle infrastructure are often tagged as part of the cycle track they are actually interrupting.

Declustering

To decluster the partially overlapping gaps identified by the IPCC procedure, we developed a simple declustering heuristic, which is described in Box 2. Within the declustering process, gaps with a benefit metric of at least $B(g)_{\min}$ are combined into a network C , after which each disconnected component of C is declustered separately. Declustered gaps are added to the declustered gap list d . Gaps that obtain a benefit metric below $B(g)_{\min}$ are discarded. The list of remaining gaps is the output of the declustering heuristic and the input for the next step in the IPCC procedure (classification).

In the present study, the benefit metric of $B(g)_{\min} = 15\,000$ is used as cut-off value, which results in a list of 1199 gaps as input for the declustering heuristic. The gap network C consists of 101 disconnected components (gap clusters). The resulting gap set contains 168 declustered gaps, out of which 34 are discarded due to their lower values of $B(g) < B(g)_{\min}$; the final output d is a list of 134 gaps.

Input: List c of partially overlapping gaps; cut-off benefit metric $B(g)_{\min}$

Output: List d of non-overlapping gaps

```

Remove gaps with  $B(g) < (g)_{\min}$  from  $c$  ;
Combine gaps  $c$  into network  $C$  ;
Decompose network  $C$  into a list of disconnected components  $dc$  ;
for  $comp$  in  $dc$  do
    while  $comp$  is not empty do
        compute all shortest paths between nodes  $n \in comp | d(n) \neq 2$  ;
        compute benefit metric  $B(g)$  for each path ;
        find path  $p_{\max}$  with highest value  $B(g)_{\max}$  ;
        add  $p_{\max}$  to final gap list  $d$  ;
        remove  $p_{\max}$  from  $comp$  ;
    end
end
Remove gaps with  $B(g) < (g)_{\min}$  from  $d$ 

```

Box 2: Declustering heuristic for overlapping gaps

Appendix B: Error plot

FIGURE 12 Errors in the list of top ranked gaps in Copenhagen. 29 out of 134 gaps identified by the IPCC procedure in the Copenhagen network that have been discarded as errors: data issues in light blue; parallel paths in light green.

Appendix C: Gap plots

Table 2 contains close-up maps of all 105 prioritized gaps from the Copenhagen case study, with the city map as background layer. Gaps are sorted by ranking, from highest to lowest value of the benefit metric B . The benefit metric B indicates the number of meters cycled in motorized traffic that can be avoided per investment unit if a gap is “closed”. The network of protected bicycle infrastructure is shown in black. Gap classes are indicated by abbreviations and distinguished by plotting color:

- █ ST Street (orange)
- █ IS Intersection (yellow)
- █ RT Right-turn lane (pink)
- █ BR Bridge (red)
- █ RA Roundabout (violet)

TABLE 2 Top 105 gaps: Details

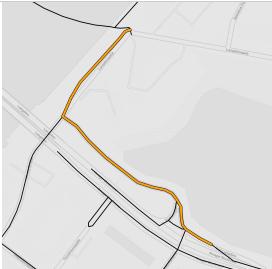
Detail map	Ranking	Benefit B	Class	Address
	1	65,252	BR	Knippelsbro
	2	39,447	IS	Øster Voldgade / Sølvgade
	3	37,565	IS	Enghavevej / Vigerslev Allé

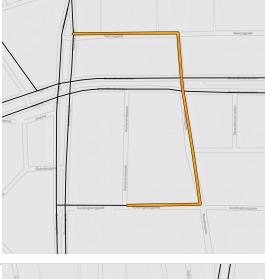
Detail map	Ranking	Benefit B	Class	Address
	4	37,308	ST	Jacob Erlandsens Gade
	5	36,498	ST	Tåsingegade
	6	36,278	RT	from Øster Allé to Nørre Allé
	7	34,726	ST	Hans Knudsens Plads / Glænøgade / Æbeløgade
	8	33,653	BR	Langebro

Detail map	Ranking	Benefit B	Class	Address
	9	32,246	RT	from Backersvej to Øresundsvej
	10	31,742	ST	C. F. Richs Vej / Bernhard Bangs Allé
	11	29,347	ST	Griffenfeldsgade
	12	29,145	ST	Aldersrogade
	13	28,745	ST	Værnedamsvej

Detail map	Ranking	Benefit B	Class	Address
	14	28,645	RT	from Hillerødgade to Borups Allé
	15	28,568	ST	Vermundsgade
	16	28,342	ST	Tschernings Allé
	17	27,495	ST	Ålandsgade and Frankrigshusene
	18	27,405	ST	Blegdamsvej

Detail map	Ranking	Benefit B	Class	Address
	19	26,933	RT	Christians Brygge
	20	26,311	IS	Alekistevej with Jyllingevej
	21	25,607	ST	Thorvaldsensvej
	22	25,568	ST	Sigynsgade
	23	25,543	ST	Hamletsgade

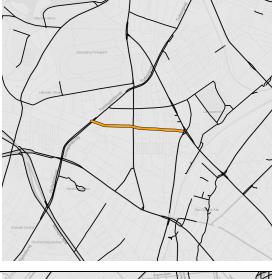
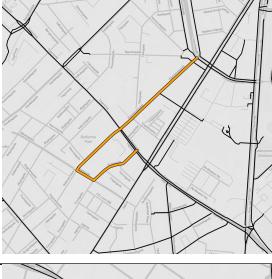
Detail map	Ranking	Benefit B	Class	Address
	24	25,534	ST	Kristen Bernikows Gade / Nikolaj Plads / Højbro Plads
	25	25,067	ST	Christian IX's Gade
	26	24,565	ST	Koldinggade and Randers-gade
	27	24,148	ST	Langebrogade and Ved Langebro
	28	22,942	ST	Øster Farimagsgade

Detail map	Ranking	Benefit B	Class	Address
	29	22,910	ST	Borgmester Fischers Vej
	30	22,770	ST	Gåsebæksvej
	31	22,769	RT	from Nørre Allé to Øster Allé
	32	22,144	ST	Nyborggade, Randersgade and Vordingborggade
	33	21,856	ST	Sofus Francks Vænge

Detail map	Ranking	Benefit B	Class	Address
	34	21,688	ST	Dybbølsgade
	35	21,626	ST	Tietgensgade, Helgolands-gade and Colbjørnsensgade
	36	21,606	ST	Blågårdsgade
	37	21,599	IS	Peter Bangs Vej with Linde-vangs Allé
	38	20,995	ST	Annexstræde and Rughavevej

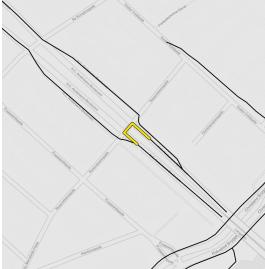
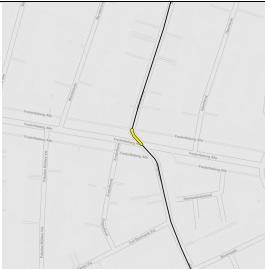
Detail map	Ranking	Benefit B	Class	Address
	39	20,990	ST	Herlufsholmvej
	40	20,952	ST	Nordre Frihavnsgade
	41	20,518	RA	Australiensvej/Bryggerivangen and Sankt Kjelds Plads
	42	20,484	ST	Christen Bergs Allé
	43	20,464	ST	Vendersgade

Detail map	Ranking	Benefit B	Class	Address
	44	20,202	IS	Skellet with Roskildevej
	45	20,194	ST	Forhåbningsholms Allé, Carl Plougs Vej, Julius Thomsens Plads and Julius Thomsens Gade
	46	20,090	ST	Valløvej
	47	19,622	IS	Enghavevej / P. Knudsens Gade
	48	19,545	IS	Sølvstorvet

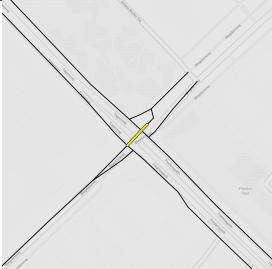
Detail map	Ranking	Benefit B	Class	Address
	49	19,503	IS	Hammerichsgade and Vesterbrogade
	50	19,171	ST	Store Kongensgade
	51	19,096	ST	Birkedommervej and Landsdommervej
	52	18,988	ST	Rådmannsgade, Mimersgade and Thorsgade
	53	18,965	ST	Ørnevej and Mågevej

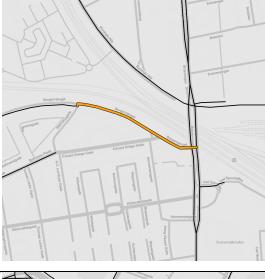
Detail map	Ranking	Benefit B	Class	Address
	54	18,941	ST	Gamle Vasbygade
	55	18,812	IS	Fensmarkgade with Tagensvej
	56	18,531	ST	Kronprinsesse Sofies Vej
	57	18,331	ST	Østbanegade and Bergens- gade
	58	18,254	ST	Rantzausgade, Kapelvej, Hans Tavsens Gade

Detail map	Ranking	Benefit B	Class	Address
	59	18,117	RT	from Søndre Fasanvej to Smallegade
	60	18,116	ST	Strandboulevarden
	61	17,993	ST	Valby Langgade and Gammel Jernbanevej
	62	17,927	ST	Oxford Allé
	63	17,778	ST	Frilands Allé

Detail map	Ranking	Benefit B	Class	Address
	64	17,693	IS	Ellebjergvej with Gammel Køge Landevej
	65	17,597	IS	H. C. Andersens Boulevard with Rysensteensgade
	66	17,455	ST	Bernstorffgade
	67	17,392	IS	Kingosgade with Frederiksberg Allé
	68	17,362	ST	Engvej, Sorrentovej and Backersvej

Detail map	Ranking	Benefit B	Class	Address
	69	17,319	ST	Nørregade, Gammeltorv, Nytorv, Rådhusstræde and Frederiksholms Kanal
	70	17,290	ST	Kronprinsessegade
	71	17,290	ST	Gustav Johannsens Vej
	72	17,181	ST	Ib Schønbergs Allé
	73	17,071	ST	Lygten

Detail map	Ranking	Benefit B	Class	Address
	74	16,907	ST	Mågevej
	75	16,897	ST	Retortvej
	76	16,869	IS	Blegdamsvej with Tagensvej
	77	16,855	ST	Guldbergsgade
	78	16,766	IS	Gammel Kongevej with Henrik Steffens Vej

Detail map	Ranking	Benefit B	Class	Address
	79	16,762	ST	Solvej
	80	16,758	ST	Frederiksberg Allé, Platanvej and Vesterfælledvej
	81	16,730	ST	Sibeliusgade
	82	16,533	ST	Vester Farimagsgade (north)
	83	16,530	ST	Stadfeldtsvej, Ole Borchs Vej and Høffdingsvej

Detail map	Ranking	Benefit B	Class	Address
	84	16,530	ST	Drosselvej
	85	16,506	ST	Korsager Allé
	86	16,420	ST	Kortløb
	87	16,389	RT	from Ågade to Borups Plads
	88	16,331	ST	Tranehavevej

Detail map	Ranking	Benefit B	Class	Address
	89	15,846	IS	Toftegårds Plads with Vigerslev Allé
	90	15,804	ST	Stefansgade, Gormsgade, Mimersgade and Baldersgade
	91	15,770	ST	Sigurdsgade
	92	15,717	BR	Langebro (other side)
	93	15,652	ST	Jernbanegade

Detail map	Ranking	Benefit B	Class	Address
	94	15,650	ST	Shetlandsgade
	95	15,597	IS	Børsgade with Holmens Bro
	96	15,585	ST	Vester Farimagsgade (south)
	97	15,557	ST	Rialtovej
	98	15,528	ST	Peder Lykkes Vej, Prinsesse Christines Vej and Højdevej

Detail map	Ranking	Benefit B	Class	Address
	99	15,497	ST	Lergravsvej
	100	15,440	ST	Bagerstræde
	101	15,435	ST	Æblevej
	102	15,376	ST	Strømmen
	103	15,365	ST	Straussvej

Detail map	Ranking	Benefit B	Class	Address
	104	15,365	IS	Mellemvangen Hareskovvej with
	105	15,323	ST	Lyshøjgåardsvej