Efficient bicycle networks and expansion strategies

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Abstract

This article explains some of the key attributes and factors relating to efficient bicycle networks and their expansion strategies. Varying from a network scale to brief discussion about the streetscape design, many scientific publications are referenced to explain the crucial aspects which must be taken into consideration when planning an attractive cycling network. Modal switch from other transport modes, especially from cars is one of the goals of this cycling promotion. Various methods such as building new bicycle facilities, improving the quality of existing ones and increasing the comfort and safety of the connections were found to improve the attractiveness of cycling in urban context. Additionally, this article analyses the reasons behind cyclists' route choice as well as the metrics such as connectedness, directedness and coverage which can be used to measure the level of network functionality. Lastly, network growth under limited resources is considered and an equitable distribution of cycleways across the city is found to be important in preventing neighbourhood segregation while not being too far from a utilitarian kind of distribution in terms of return to investment.

1. Introduction

Cycling has been a part of urban mobility for a long time, but it has been seen differently through the times. In the 21st century, however, cycling is largely connected to climate-friendly modes of transport and therefore the political push for the increase of the share of cyclists in cities can be seen especially in some European countries. Many methods have been tried to encourage people into cycling. According to Buehler, R & Dill, J. (2016), almost all cities that have attempted to do so have expanded bike networks, including bicycle lanes, cycle tracks and traffic calming of neighbourhood streets. Therefore, the analysis of bicycle network efficiency and expansion plays a key role in this large context of cycling promotion. As one of the key methods has been the construction of bike-specific lanes and roads, the effect of these should be evaluated as precisely as possible.

This essay will cover some of the key concepts relating to bicycle network's functionalities both from street level and network level, concentrating more on the network level. At first, we will introduce the context in which cycle networks play a key role, secondly, we will introduce one type of theory which presents the maturity of cycle networks in each city as well as discuss the improvements which should be done first to promote cycling on each level. After those, we analyse more deeply the reasons behinds cyclists' route-choice and which attributes of cycle networks are most crucial in terms of cycling promotion. On the fourth chapter we discuss the evaluation methods of existing bicycle networks and critically analyse their effectiveness from a given viewpoint. Finally, the distribution of limited resources invested in bicycle networks is considered ending with conclusion.

1.1 The role of network expansion in attracting cyclists

Buehler, R & Dill, J. (2016) analysed numerous publications relating to cycling networks especially in the United States. Even though some studies did not find correlation between the length of the bicycle network, none of them argue that constructing more bike lanes would decrease the popularity of cycling. On the other hand, Dill, J & Carr, T. (2003) found from their study of 42 large US cities that each additional linear mile of bike lanes per square mile land area was associated with a roughly 1% increase in share of bike commuters. From this result, some connections were missing in the bike networks of these cities. Cities in the United States mostly are not built solely for prioritizing cycling and therefore would put them at most to the level 3 of bicycle cultural maturity which is explained in more detail later. One percent increase in the share of bike commuters obviously cannot be infinite as there would be a point where constructing a new bike lane would not benefit large numbers of commuters to change from a car e.g., to a bike. However, in cities where coherent bike networks are lacking, this could very well be one of the first steps towards a more bike-friendly city.

2. Bicycle maturity and bicycle network needs

Different cities are at different maturity levels regarding their bicycle culture and infrastructure. Thus, the next logical step for a network expansion depends on what maturity level the city is at. As an example, connecting missing links works well for cities that have some kind of bicycle network but are lacking connectivity, whereas those cities that already have a well-connected network can focus on improving travel comfort and speed, e.g., by investing into cycling superhighways. Building high-speed and high-capacity links is not always optimal for cities that are at low stages of bicycle maturity. These cities should instead focus on providing adequate connections between main locations and residential areas, which will allow the bicycle culture to develop and the user base of cyclists to grow.

The bicycle network needs follow some kind of hierarchy, where a limited budget should be first allocated to building basic components of the network, and at later stages of maturity emerged needs, such as the need for mitigating congestion, can be tackled. Reggiani et al. (2022) have proposed a theoretical need-driven framework that draws inspiration from Maslow's (1943) hierarchy of human needs, often represented as a pyramid. Just as the bottom layers of the Maslow pyramid, the bottom layers of the proposed bicycle network needs pyramid must be adequately satisfied before higher-order needs become relevant. Reggiani et al. (2022) defines five levels of bicycle culture, and their corresponding hierarchical bicycle network needs as follows (figure 1):

- 5. Bike dominant – Mitigate congestion
- 4. Bike friendly – Comfort
- 3. Bike emerging – Connectivity
- 2. Bike ignorant – Safety and accessibility
- 1. Bike hostile – Basic and direct paths

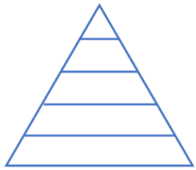

Figure 1: Reggiani et al. (2022) defines five levels of bicycle culture, and their corresponding hierarchical bicycle network needs.

A bike hostile city is mainly focused on car mobility, and it is lacking in the very basics of bicycle infrastructure. According to Reggiani et al. (2022), bike hostile cities require direct and well-known bike connections between the most important parts of the city. The way to move away from the lowest tier of bicycle culture is to build fast and build cheap: to redistribute the existing road space instead of building segregated bike paths. Bike sharing fleets may already be established at this stage.

A bike ignorant city already has an interest in developing bicycle culture but is lacking in coherent network planning. This kind of city should simultaneously look at increasing safety and accessibility of the network. Safety in this case means reducing the chances of crashes by, e.g., limiting the speed of cars, investing in lighting, and setting up separate traffic signals for cyclists. Increasing accessibility means building infrastructure to locations where it has the best chances of offering communities a basic level of bicycle accessibility.

A bike emerging city has some plans for cycling mobility but has a network that is not yet well connected. Emerging bicycle cities have many possible paths for expansion, but only through careful analysis and planning can they choose the most effective way forward. The key things they should understand are the latent cycling demand and the weak links of the infrastructure. By understanding latent demand, it is possible to maximize the number of new users with minimal investments, and by identifying weak links (or missing components), it is possible to increase overall connectivity in the city.

A bike friendly city has already a well-connected network, and relatively comfortable and safe cycling. It can focus on further increasing the bicycle modal share by improving route guidance, improving traffic control, and further prioritizing the bicycle mode in traffic. It can also integrate cycling better to public transport to encourage multi-modal trips.

A bike dominant city has a very mature cycling culture, even to the point that there are new kinds of problems. The volumes of cyclists start to exceed the capacity of the cycleways, which decreases the perceived safety and comfort. In these cities, congestion mitigation and rethinking of road space are necessary to facilitate the high volumes. Network expansions in new locations are rarely needed at this stage.

3. Cyclists' route choice and its effects on modal split

One of the main features of cycling is that moving a bike requires muscular force excluding bikes that are fully electric. This feature itself sets many requirements for a well-balanced and tempting bicycle network. In addition, the speed and vulnerability of a cyclist are attributes that ultimately affect many different factors relating to the attractiveness and comfort of cycling. Broach, J, et al. (2012) and Dill, J. (2009) in their papers concretize the attractiveness of bicycle facilities with the number of cycled kilometres in Portland, Oregon in the United States. According to them, using a GPS device to track cyclists, it was found that 50% of the cycled kilometres occurred on roadways whereas the other half occurred on bicycle facilities even though they only accounted for 8% of the bikeable road network. This results itself presents the fact that cyclists appreciate paths specifically designed for bikes. Examples of factors which could be analysed relating to bike networks to evaluate the quality of a given network are presented in more detail later. However, some attributes that affect the route choice of cyclists are the number and type of intersections, grade of the road, number of lanes, condition of the road, length of the connection and perceived feeling of safety.

Analysing the whole bicycle network instead of just single links is important when trying to improve the share of cyclists in urban areas. This relates to the route choice options and differences between the available routes. Intersections for instance usually have a negative effect on cycling experience (Buehler, R & Dill, J., 2016). As mentioned earlier, muscular force is required to move a bicycle which means that all stops on a cycle route increase the physical workload required. This includes intersections with traffic lights and stop signs but also nodes where cyclists must decrease speed to travel safely. These interruptions to a cycling trip negatively affect the attractiveness of a given route and may cause some deviations for a cyclist and ultimately distort the modelled cycling routes if these attributes are not considered thoroughly. Crane et al. (2017) explain that according to reveal preference of cyclists, they are willing to deviate from the most efficient routes to commute on safer roads. This claim, however, works only to an extent. The problem of having a safe but also an efficient cycle route could be solved by separation of traffic modes, especially cyclists from other modes. However, the separation of traffic modes should not be done with the expense of a dramatic travel time increase and decrease in efficiency. For example, a study done in Vancouver, Canada found that 90% of non-recreational cyclists' trips were withing 25% of the shortest route distance (Winters, M et al., 2010). This percentage would obviously vary between cities regarding their network capabilities but the fact that only 10% of these cyclists were willing to deviate more than 25% is prominent information for cycling network planners.

4. Network metrics

Evaluation of a cycling network is a critical part of building a coherent and well-balanced part of infrastructure which ultimately promotes cycling. As the effects of such an infrastructure are long-lasting, evaluation of the existing network should be done already in the early stages of its lifespan. This way the future construction can be done iteratively so that the future cycle network projects are getting increasingly better than before. The biggest problem in this evaluation, however, is that there are many types of cyclists who all have different preferences relating to cycling. This results in a situation where compromises must be made. In academic literature some, methods of evaluating the networks include for example trying to formulate coefficients to various preferences or by measuring attributes that are found to affect the attractiveness of cycling. This section will qualitatively introduce some metrics used to measure the performance of specific bicycle network attributes. Based on these metrics and research on cyclist preferences, bicycle facility investments can be allocated in a data-driven manner, and in some sense, most efficiently.

4.1 The main types of metrics and related network improvements

Much of the contemporary research on network-wide scale is computational, which has produced quite an abundance of mathematical expressions. Naturally, it is not simple to mathematically represent some of the ultimately experiential features. Furthermore, it is hard to say which exact metrics should be used, because they might fit different purposes: some of them could be computationally simple, some of them could fit the purpose of multi-modal transport planning than others, and ultimately the context of the city determines the most applicable measure. By researching the literature, we have identified some of the main groups of metrics that could be incorporated in planning processes in some form or another.

Orozco et al. (2020) use connectedness and directness as the main metrics in their algorithmic study that aims to suggest optimal investment strategies. Boisjoly et al. (2020) use route deviations, network connectivity, and the proportion of route travelled on bicycle facilities. Szell et al. (2022) use the following quality metrics in their algorithmic growth models: length, length of the largest connected component, coverage, directness, number of connected components, and local and global efficiency (related to directness). Vybornova et al. (2022) use gaps, gap clusters, and detour-based measures to identify missing links in networks.

It seems that the most common measures are related either to connectedness (which is the opposite of gaps), coverage, or directness (which is the opposite of route deviations). However, the studies mentioned above use algorithms that don't discriminate between low-quality and high-quality links, so an apt critique is whether they measure the quality of the infrastructure itself enough. Therefore, in addition to the previously mentioned, we would suggest including a quality metric that includes the safety, comfort, and speed of the individual links. Next, the main groups of metrics are introduced in more detail.

4.2 Connectedness

Connectedness is the measure of how continuous the bicycle infrastructure is, or in other words, how little fragmentation there is. Connectedness is related to the question of can one go to their destination safely and on dedicated infrastructure (Orozco et al., 2020), with no particular concern about travel time or distance travelled. As discussed in section 2 about bicycle network needs, the first steps a city takes in developing its bicycle network are not, and perhaps shouldn't be, about increasing connectedness. Rather, the low maturity cities should be somewhat opportunistic in taking inexpensive steps at expanding their network and/or building facilities between high-demand locations. This leads to a fragmented network with smaller and larger components but not necessarily interconnected with one another. After the main network pieces are built, the cities should aim to connect the components to enable more trips on dedicated infrastructure. The following illustration by Vybornova et al. (2022) supports this idea, where the undeveloped cycling cities need not worry about connectedness, bike-emerging cities can increase connectedness by tying fragmented pieces together, and beyond bike-emerging cities can focus on directness-improving connections that fill in missing links, simultaneously building redundancy and resiliency in the network. They mention Los Angeles as an example of an undeveloped city (on the left in Figure 2), Budapest as a city with a fragmented network (middle), and Copenhagen as a city with an already well-connected network (right).

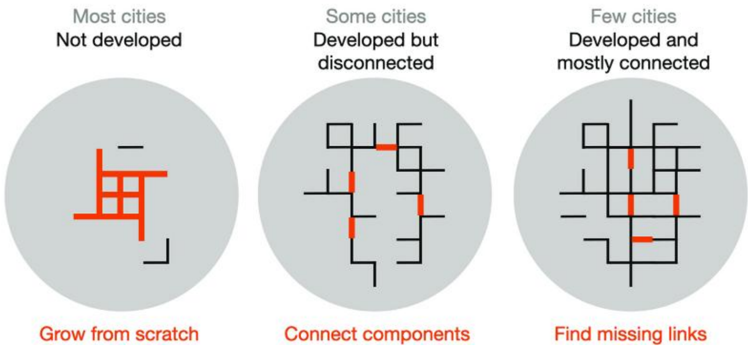

Figure 2: The role of connecting fragmented components and filling in missing links in different cities (Vybornova et al., 2022).

Vybornova et al. (2022) approach the problem of increasing connectivity in Copenhagen by identifying gaps at streets (a street that has no protected infrastructure but connects two parts of protected infrastructure), intersections, right-turn lanes, bridges, and roundabouts. The common factor in these gaps seems to be that there is an underlying idea to connect two parts of the city, but due to construction difficulties or high costs, the gap part did not get protected bicycle lanes.

4.3 Coverage

Coverage measures the percentage of either the area or the population of the city that has accessibility to the bicycle network, for example in a 200-meter radius. Coverage is related to connectedness in the sense that coverage of a fully connected network is better for the residents than coverage of any random segments. Whether or not to increase coverage, is somewhat a value-based decision and is related to land-use planning and distributive considerations, as will be discussed in section 5.2.

4.4 Directness

Directness is in its simplest form, the ratio between Euclidean distance and shortest path distance between two points (Szell et al. 2022). Directness is one of the most important attributes of the network, because if the route is not direct, cyclists may opt for a more direct but unsafe route with mixed traffic. In a stated preference survey, Stinson & Bhat (2003) found that commuter cyclists strongly prefer directness on route to their workplace, however, they are also willing to make slight detours to use bicycle facilities.

Directness can be measured not only for bicycle networks in isolation, but as bicycle-to-car directness. This measure controls for the unavoidable low directness in special geographical cases, such as hilliness and water bodies. The directness along bicycle network is compared to the directness along the network allowed for cars. For example, Orozco et al. (2020) define bicycle-to-car directness as the ratio between average car route distance and the average length of the shortest bike route.

4.5 Quality of the path

Connectedness, coverage, and directness are not enough to explain travel behaviour, because the quality of the path for which these attributes are calculated, can vary a lot. For example, the algorithmic approaches introduced before, often do not consider the safety, comfort, and speed of individual links. Furthermore, the choice of a particular route often depends on the next-best option, so one needs to evaluate what is the difference between taking a detour on bicycle-dedicated bike lane and going straight on a mixed traffic street.

Some of the quality attributes that could most easily be included in computational models include inclines, number of intersections, number of traffic lights, car traffic volume, and the maximal speed that the path allows. As an example of the possibilities, in estimating the adequacy of a particular route for daily commuters, one could incorporate a perceived exertion model that uses elevation data along routes to calculate the perceived physical effort (Carl et al., 2013).

4.6 User preferences between the metrics

There is no one metric or criterion that clearly dominates the others in all possible senses. For example, it depends on the trip purpose, the physical health, safety preferences, among other things, whether directness is preferred over continuous protected infrastructure. Furthermore, many things, such as the coverage of the network, is also a matter of local politics and spatial planning. Some idea of the ranking of route attributes for commuter cyclists was found in a stated preference survey by Stinson & Bhat (2003). They found that commuters prefer, in order of importance: lower travel times (perhaps most closely linked to directness), residential roads over major and minor arterials (indicating that traffic calming is effective), bicycles facilities over non-bicycle facilities (emphasizing connectedness), bridges having protection for cyclists, smooth pavement, streets with no parallel parking, fewer major cross streets, flat ground, continuity of bicycle facility over an interrupted one, fewer stop signs, and finally fewer red lights.

5. Bicycle network growth under limited resources and distributional considerations

Realistically, bicycle lanes cannot be built on any of the streets. The volume of motorized traffic, available space for widening the road, the number of intersections, among other things, place constraints on which streets are the most suitable for placing a bicycle lane in. For a moment, however, let's assume that such constraints don't exist, and the optimal growth is only based on how the network topology at large creates welfare by connecting locations and how much it costs. Analysing the costs and benefits on a more generalized level allows to later add to the equation the specific constraints of each location and justify decisions based on a comprehensive analysis of network-wide effects as well as local effects in addition to investment costs. In this section, we will consider how the general shape and structure of the network affects the distribution of benefits among different stakeholders and communities.

5.1 Trade-offs associated with the general shape of the network

The following illustration (Figure 3) by Szell et al. (2022) shows not only how different network shapes are desirable from the points of views of the investor and the traveller, but how there is a trade-off between economizing and building resilience. The solution that connects the most locations with minimum path length, is called the minimum spanning tree. This arrangement provides the maximal cost-efficiency if the only goal is to connect the main points of interest with a bicycle path. While this arrangement could in some circumstances minimize the cost per travelled kilometre, it has some significant downsides. It provides less direct routes, which compromises the competitiveness of the bicycle mode, and thus reduces some of the user attraction, which is not desired if the city plans to increase the number of cyclists. The minimum spanning tree could also prioritize already developed areas while ignoring under-developed ones (Mahfouz et al., 2021; Szell et al., 2022), which could reinforce the socioeconomic inequalities among these neighbourhoods and contribute to segregation. The resiliency of this network is low because an interruption, such as a roadwork, cuts the entire network into disconnected pieces (Szell et al., 2022). If the goal is to make a city bikeable around the year, this kind of network requires a large effort into planning and establishing alternative cycling routes in case of interruptions. Based on these arguments, Szell et al. (2022; p. 2) criticize the fact that a large share of current computational research is geared towards connecting missing links in bicycle infrastructure, which often leads to suboptimal minimum spanning tree-like solutions.

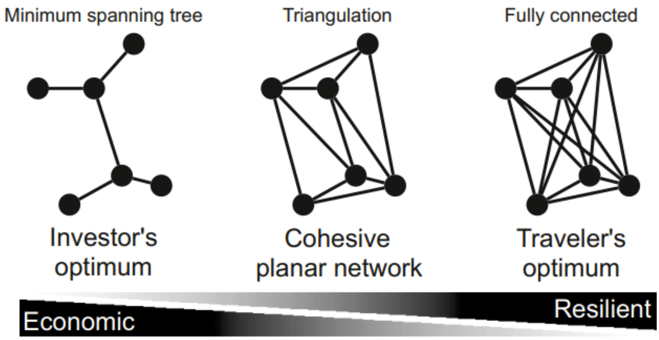

Figure 3: Illustration of the trade-off between economizing and building resilience in different network topologies (Szell et al., 2022).

On the other end of the spectrum, there is the traveller's optimal network. This network provides maximal directness, so it is the best we can do in terms of attracting people to the cycling mode. It is also maximally resilient and provides access to even some of those underserved neighbourhoods that don't have any regional points of interest. However, this network in all its redundancy, could have the highest cost per travelled kilometre because the utilization rate of any single path is smaller. In between the investor's and traveller's optimal networks, there exists an array of intermediate solutions, including the triangulation approach used by Szell et al. (2022) in their computational bicycle network growth algorithms. The intermediate solutions provide a fair amount of directness, and a fair amount of resiliency by offering at least two routes between any two points, while still being reasonably inexpensive to build.

5.2 Utilitarian and egalitarian expansion

It is not only the shape of the network, but also the location of it, that has consequences on bicycle accessibility throughout the city. It is tempting to concentrate new bicycle infrastructure in locations that are already bike-emerging, as there are still a lot of potential cyclists to attract in these locations, and enhancements greatly improve the comfort for existing cyclists. However, prioritizing always the highest-demand routes could eventually lead to an uneven distribution of investments across neighbourhoods. For instance, an expansion strategy that aims to connect missing links in bicycle infrastructure could be effective in enhancing the existing network, but it is mostly the already affluent neighbourhoods that gain from this expansion. Communities that have few or none bicycle paths, would get neglected in this utilitarian expansion regime, because it is more costly to start building the network from scratch than to improve existing ones. An egalitarian strategy, on the other hand, would aim to distribute either the investment or the outcome fairly in space. This strategy could imply more immediate costs and friction in establishing a bicycle culture in the city, but perhaps it would be a more sustainable growth option that reduces long-term inequalities and segregations between different parts of the city.

As with other network attributes, also the spatial distribution of infrastructure requires deliberation of trade-offs between utilitarianism and egalitarianism. In the long-term, it is obviously good to pursue spatial equity, but under uncertain financial outlook in the future and the near-future climate crisis, it is tempting to just maximize the modal shift to cycling. Mahfouz et al. (2021) developed a road segment prioritization algorithm for cycling infrastructure, which can be applied either city-wide (utilitarian expansion) or at a community level such that the investment gets distributed proportionally (egalitarian expansion). They found that the egalitarian algorithm, while equalizing the distribution of investment, did not come at any noticeable cost of less connectivity or less city-wide gains. This result suggests that maybe it is not so "anti-utilitarian" to be egalitarian after all.

6. Conclusion

The current bicycle networks in cities differ significantly, however, there are many strategies to improve these existing networks as well as expand them to provide larger coverage of bicycle facilities. Analysis and evaluation of cyclists' route choices and various preferences are an essential for planners to understand this complex problem of cycle networks. Methods for such a planning require a deep understanding of individuals and their revealed preferences as well as hopes for the future.

Whichever is the city's desired shape and coverage of the network and the associated outcomes, it is evident that to reach certain objectives, one must plan on a network level. This planning is a multi-objective problem, where each city has its own constraints and prospects. First, the bicycle network does not exist in isolation from the other transport system, so developing it efficiently could require making changes also in car traffic (traffic calming, street space reallocation) and public transport (integration to cycling in terminals and vehicles). Second, the bicycle network itself has multiple attributes and metrics which influence the attractiveness of cycling.

These include, e.g., directness, coverage, connectivity, safety, low physical and mental stress, and allowed travel speed. Third, the performance of the network can also be measured from multiple non-traveller points of view, including resiliency, equitability, and cost-effectiveness.

Our readings have provided articles on computational methods to assess performance by some particular network metrics (Boisjoly et al., 2020; Carl et al., 2013; Mahfouz et al., 2021; Szell et al., 2022; Vybornova et al., 2022), articles that explore empirical cyclist preferences between network qualities (Broach et al., 2012; Buehler & Dill, 2012; Crane et al., 2017; Dill, 2009; Dill & Carr, 2003; Nello-Deakin, 2020; Stinson & Bhat, 2003; Winters et al., 2010), as well as one article providing strategic guidelines for network expansion in different cities (Reggiani et al., 2022). The common finding across most of these articles is that all the previously mentioned network attributes matter, but directness is ultimately the most dominant one due to its effect on travel speed. A cyclist is willing to accept less safe and comfortable cycling environment if it makes the route significantly shorter. However, other attributes such as coverage, connectivity, and protected infrastructure, can be influential in attracting new bicycle users (matching latent demand in the city).

We found that the order of improvements matters when making a shift from a car-friendly city to a bicycle-friendly city. According to Reggiani et al. (2022), going from low level of bicycle-maturity to high bicycle-maturity, the preferred order of infrastructure expansion is building direct facilities between most important locations first, then increasing the spatial coverage of the network, then increasing connectivity by bridging missing links, and finally when most of the expansion is done, making capacity and comfort improvements to the existing facilities. According to results of Mahfouz et al. (2021), it is plausible that equitable spatial distribution of facilities is not always in conflict with "utilitarian expansion", indicating that could be room for incorporating egalitarian principles in network growth strategies. However, there is possibly a trade-off between cost-effective expansion and an expansion that builds resilience (Szell et al., 2022).

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