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Prioritizing the Gaps: Including Equity in Bicycle Infrastructure Planning

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Abstract

The urgency of the climate crisis emphasizes the importance of reducing greenhouse gas emissions, a goal that cities intend to achieve by developing their cycling infrastructure. However, sustainability includes social equity, and transport has been shown to play a role in reinforcing urban inequalities. This study seeks to understand how cycling infrastructure can be developed to reduce greenhouse gas emissions and urban inequalities by assessing emerging equity-induced trade-offs in prioritizing cycling projects within the Grand Paris Metropolis, France. By combining automated identification of cycling infrastructure gaps with equity frameworks, this research identifies shifts in the prioritization of infrastructure projects based on degrees of equity emphasis. The focus lies on vulnerable populations, specifically children commuting to school coming from neighborhoods with lower educational attainment and adults commuting to work from neighborhoods with lower median income. The outcomes reveal that introducing equity considerations impacts the order of importance of infrastructure projects, though the overall trajectory remains intact, suggesting that integrating equity into transport planning is an achievable goal.

Executive Summary

The urgency of the climate crisis has led to a focus on environmental sustainability in urban development. In this context, reducing pollution and especially greenhouse gas (GHG) emissions has become crucial, given their contribution to global warming [D'Amato et al., 2014]. Urban transport planning has prioritized less polluting modes of transport such as cycling, which can play a significant role in reducing car use [Kuhnimhof et al., 2012] and, consequently, GHG emissions.

The exclusive focus on reducing pollution and GHG emissions has led to a neglect of equality concerns, which are a crucial part of social sustainability [Martin, 2019]. Cities are known for complex, compounded, and multifaceted inequalities, with the gap between the best- and worst-off widening with city size [Sarkar, 2019]. Transport can either reinforce or combat these inequalities [Calderón and Servén, 2014, van Wee and Geurs, 2011], highlighting the need for urban transport planning to address both GHG emission reduction and equality concerns to create truly sustainable cities. This can only be done if we move away from utilitarianism, the backbone of Cost-Benefit Analysis, a standard in policy-making.

This research aims to take the first step towards understanding how to incorporate equity into transport planning by analyzing the trade-offs that arise when simultaneously focusing on equity and maximizing the number of cyclists. These trade-offs must be made clear to policymakers to develop transport infrastructure that effectively achieves its goals. The research question is: **"How does including equity in transport planning change the development of the bicycle infrastructure"**, and is answered through the analysis of the case-study city of the Grand Paris Metropolis, France.

To this aim, the automated search for gaps in bicycle infrastructure as developed by Vybornova et al. [2022] is combined with the equity considerations developed by Yap et al. [2021] and Jafino et al. [2021] in order to identify which possible future pieces of infrastructure should be prioritized depending on how strongly equity is considered. The inclusion of equity is done through the identification of vulnerable populations for the scenario of children commuting to school and for the scenario of adults commuting to work. Those trips were chosen because it has been shown that cycling infrastructure can most effectively reduce GHG emissions if it is used to commute, and the vulnerable populations, in this case, are children living in neighborhoods with low average educational attainment and adults living in neighborhoods with low median income.

The results show that introducing equity influences the order in which infrastructure projects should be prioritized, but it does not change said order beyond recognition. Regardless of the scenario or equity, the most important gaps to close in our results are those along the main ring road circling Paris, followed by long roads linking suburbs to said ring road. The introduction of equity replaces the prioritization of some small gaps on the ring road with that of bigger gaps outside of the city, usually in neighborhoods with low median income. The mild change in priorities despite including equity considerations is promising as it means that only minor changes are required in current ways of planning transport in order to properly introduce equity and properly serve underprivileged communities.

Despite the promising results of this study, further research could improve the model and the methods used here. For example, the use of simple algorithms such as a shortest-path algorithm on such a complex network may be oversimplifying the results, some steps of the calculations such as the declustering heuristic could be improved, and our approach is applying Vybornova et al. [2022]'s methods on a vastly different network than these methods were developed for. Any changes in these three aspects of our research could significantly change the outcomes of the experiments. Similarly, our definitions of equity and vulnerability could be debated and refined, and this change in definition could lead to different results depending on the numerical distribution of the related data, as the model seems to be quite sensitive to such details.

Overall, this research has the following main implications:

1. Models based on purely quantitative methods can lead to undesired negative consequences for society, and expanding them to consider these consequences is not an insurmountable task. We encourage scientists and modelers from quantitative fields to expand their work, considering the societal implications of their research and models to better society.
2. Lifting vulnerable populations out of their situation is not completely at odds with utilitarian goals, the standard in policy-making. We thus call on policy-makers to start taking equality seriously in their work.

Contents

1. Introduction

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs) [UN General Assembly, 2015]. While all SDGs should be pursued with equal importance, the urgency of the climate crisis, as highlighted by the Intergovernmental Panel on Climate Change [2022], has led to a focus on environmental sustainability in urban development. In this context, reducing pollution and especially greenhouse gas (GHG) emissions has become crucial, given their contribution to global warming [D'Amato et al., 2014]. In the European Union (EU), the transport industry has been the second most polluting sector since 2009 and was responsible for 18% of GHG emissions in 2019 (EEA 2019). This explains why urban transport planning has prioritized less polluting modes of transport such as cycling, which can play a significant role in reducing car use [Kuhnimhof et al., 2012] and, consequently, GHG emissions.

However, the exclusive focus on reducing pollution and GHG emissions has led to a neglect of equality concerns, which are a crucial part of social sustainability [Martin, 2019]. While cities offer improved opportunities and consumption, they are also characterized by disparities in accessing these opportunities, with the gap between the best- and worst-off widening with city size [Sarkar, 2019]. Transport can either reinforce or combat these inequalities [Calderón and Servén, 2014, van Wee and Geurs, 2011], highlighting the need for urban transport planning to address both GHG emission reduction and equality concerns to create truly sustainable cities. Fortunately, a growing body of research on developing equitable transport systems exists and is explored later in this document.

Currently, there is no research or policy guideline on how to combine environmental and equality concerns when planning the development of new bicycle infrastructure. This research aims to take the first step towards understanding how to incorporate equity into transport planning by analyzing the trade-offs that arise when simultaneously focusing on equity and maximizing the number of cyclists. These trade-offs must be made clear to policymakers to develop transport infrastructure that effectively achieves its goals.

To this aim, the automated search for gaps in bicycle infrastructure as developed by Vybornova et al. [2022] is combined with the equity considerations developed by Yap et al. [2021] and Jafino et al. [2021], in order to identify which possible future pieces of infrastructure should be constructed first, and whether introducing equity into the considerations has any influence on that order. The research question is as follows: **"How does including equity in transport planning change the development of the bicycle infrastructure"**.

The rest of the document is structured as follows: Chapter 2 provides background and context for this research, presenting the complexities of the topic at hand and leading to the research questions. That chapter dives into what makes cycling a good candidate to reduce GHG emissions, how transport relates to urban inequalities, what the current state-of-the-art in transport modelling is and what it can mean to focus on what's "fair". Chapter 3 outlines the case study and the methods chosen to tackle the research questions. This leads to the design of experiments that may show the difference in transport planning with and without equity considerations. Chapter 4 presents the results of the experiments set out in Chapter 3, presenting trade-offs and similarities. Chapter 5 further discusses the results by interpreting the key findings while reflecting on the limitations and implications of this research, culminating in recommendations for science and for policy-making. The documents concludes with Chapter 6, where all research questions are answered.

This thesis is also the culmination of the Master programme "Engineering and Policy Analysis" at TU Delft. The program aims to teach students how to apply quantitave methods to societal issues, a skill that is applied within this research. The use of network and data science comply with the quantitative side of the requirements, while the reflection and inclusion of what is considered fair fulfills the societal issue requirement. The relevance of this research to the public domain is its contribution to the development of sustainable cities, while its scientific contribution pertains to the expansion and combination of methods from different fields.

2. Related work

This section provides the theoretical background necessary to introduce the research questions of this report. First, the necessity of reducing the use of the car by promoting the use of the bicycle is explained, with special attention given to what the bicycle infrastructure needs to provide in order to ensure that bicycle trips replace car trips. Next, urban inequalities and the role of transport in said inequalities are presented, bringing further nuance to the necessary conditions that the bicycle infrastructure needs to fulfill in order to truly contribute to sustainable cities. The current state-of-the-art in transport modeling will then be presented, followed by a discussion of how equity can be introduced in those models as well as in transport planning in general. This section is then concluded with a short summary of the findings, leading to a knowledge gap and the research questions.

2.1. How to reduce greenhouse gas emissions through cycling

2.1.1. Why cycling?

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs) [UN General Assembly, 2015]. While all SDGs should be pursued with equal importance, the urgency of the climate crisis, as highlighted by the Intergovernmental Panel on Climate Change [2022], has led to a focus on environmental sustainability in urban development. In this context, reducing pollution and especially greenhouse gas (GHG) emissions has become crucial, given their contribution to global warming [D'Amato et al., 2014]. In the European Union (EU), the transport industry has been the second most polluting sector since 2009 and was responsible for 18% of GHG emissions in 2019 European Environmental Agency [2019]. This explains why urban transport planning has prioritized less polluting modes of transport such as cycling and public transportation, and their combination into a well-connected multimodal system, which can play a significant role in reducing car use [Kuhnimhof et al., 2012] and, consequently, GHG emissions.

To facilitate the shift from cars to bicycles, it is necessary to develop proper bicycle infrastructure as it plays a pivotal role in encouraging greater cycling participation [Hull and O'Holleran, 2014]. Notably, a study by [Carboni, 2021] revealed that the development of bicycle infrastructure would also encourage women to cycle despite being currently underrepresented in the cycling community, due to their heightened concerns about safety and reluctance to share road space with motor vehicles. Proper bicycle infrastructure can thus motivate individuals to embrace cycling as a sustainable alternative to traditional commuting methods, while also helping ensure that all genders are better included.

Cycling also presents a multitude of compelling benefits besides those related to climate change mitigation. Research has revealed a positive correlation between active commuting and improved job performance in adults aged 35 to 54 [Ma, 2019], and drivers have the lowest likelihood of feeling energized and the highest odds of being late for work, while cyclists experience the highest odds of feeling energized and of being punctual [Loong et al., 2017]. Moreover, Handy and Xing [2011] point out that cycling serves as a valuable source of physical activity, and it offers a low-polluting and low-cost alternative to driving, allowing individuals without the option of driving to reach destinations that are too far to walk to or are not covered by public transit.

Research also suggests that cycling to work reduces mortality rates significantly [Oja et al., 2011, Andersen et al., 2000], and that fostering cycling skills and habits from childhood and adolescence as well as promoting healthier exercise routines in adults can have a profound impact, particularly for those who may have had limited motivation previously [Kuh and Cooper, 1992]. This potential reaches beyond physical aspects, as it can positively influence individuals on a psychological level by leading to a feeling of community with shared values, empowering individuals to overcome personal challenges [Kaplan et al., 2019].

Overall, these findings highlight the multifaceted advantages of cycling, reinforcing its role as a transformative mode of transportation with wide-ranging benefits for individuals and society alike.

2.1.2. The limits of bicycle infrastructure

Despite the host of benefits from cycling mentioned above, and the positive correlation between bicycle infrastructure and bicycle uptake [Hull and O'Holleran, 2014], simply placing bicycle lanes in a city is not enough to ensure that GHG emissions will be reduced [Brand et al., 2014]. This can be traced back to two aspects, which will be expanded upon below. First, a *shift* from cars to bicycles can only happen if the developed infrastructure is of satisfying quality and covers the trips that are usually taken by car. Second, the infrastructure development has to be accompanied by a cultural shift.

How to properly place bicycle lanes

Research by Brand et al. [2014] demonstrated that despite newly-placed bicycle lanes being well-used after two years in the UK, there was little reduction in CO2 emissions. This indicates that few individuals switched from motorized to active modes of travel and rather added cycling to their leisurely activities. From the perspective of combating climate change by reducing GHG emissions, the placement of these new bicycle lanes was a failure. Additionally, the distance cycled per capita has seen minimal change since the 1990s [Schepers et al., 2021], raising concerns about the impact of the substantial increase in cycling infrastructure. Copenhagen's and The Netherlands' experience over a century shows that bicycle usage fluctuated like in the rest of Europe, suggesting a weak correlation between infrastructure development and commuting patterns [Carstensen et al., 2015, de la Bruheze and Adri, 2000]. The widespread use of bicycles in those places must be due to more than the mere presence of infrastructure, most likely a culture or identity.

The exclusive focus on segregated bicycle paths, which are poorly integrated into traffic planning, may thus lead to underutilized bicycle infrastructure, emphasizing the need for coherent and attractive bicycle networks [Horton and Parkin, 2012].

The importance of a cultural shift

Beyond infrastructure, a cultural shift is necessary to fully embrace cycling's benefits. Handy and Xing [2011] conclude that addressing three key factors - social environment, physical environment, and individual factors - is crucial in promoting cycling. The physical environment is related mostly to bicycle lanes, encompassing convenience and linking infrastructure with transport routes. The social environment refers to what de la Bruheze and Adri [2000] highlighted: the cultural relevance and societal image of cycling are crucial to promoting it. Cities where bicycles are not seen as a nuisance and car usage doesn't contribute to social status have the highest cycling rates. Another social aspect to address is overcoming elitist barriers and democratizing cycling, which requires a system that is accessible and straightforward for the majority [Horton and Parkin, 2012]. Individual factors are difficult to address on city level. Factors other than a cultural shift or bicycle lanes that can encourage newcomers to adopt cycling include shared bicycle systems, integrating land use density with infrastructure development, and the development of other related facilities like parking and showers at the workplace [Benedini et al., 2020].

2.2. Tackling inequalities in cities

Cities are a place of immense opportunity, thanks to the concentration of various economic, social, and cultural prospects they provide [Jayne, 2005] However, these opportunities are not equally distributed among all residents. These inequalities tend to increase with city size [Jayne, 2005], and also with the levels of infrastructure development [Pandey et al., 2022]. Infrastructure plays a pivotal role in shaping urban landscapes and can unintentionally perpetuate unequal outcomes due to its durable nature. In fact, inequalities in infrastructure are alarmingly reminiscent of economic disparities [Pandey et al., 2022].

2.2.1. The complexity of urban inequalities

The development of cities cannot be truly sustainable if it continues to produce unequal outcomes. There is thus a pressing need to focus on the development of infrastructure that emphasizes equality. Inequalities in housing, income levels, educational attainment, and other aspects can compound and correlate with each other [Nijman and Wei, 2020]. For instance, even when education is made widely accessible to everyone, an individual's social background can still significantly influence their educational outcomes [Lucas, 2001].

Economic inequality in American neighborhoods is often intertwined with persistent racial and ethnic disparities [Galster and Sharkey, 2017]. However, inequalities are not solely confined within individual neighborhoods; they are also distributed spatially across urban landscapes. The location of an individual's home can predict a large share of their future economic outcomes [Chetty et al., 2014]. Social segregation tends to be more prevalent in towns where neighborhoods are situated far apart from the town center, with amenities concentrated in specific areas [Toth et al., 2021]. A study conducted in the US has shown that various dimensions of inequality are systematically organized in space [Galster and Sharkey, 2017].

Variations in economic status, labor market opportunities, education, and other relevant factors are visible across towns and metropolitan areas [Galster and Sharkey, 2017]. Such variations can lead to neighborhoods with limited access to resources being concentrated in specific areas, making it harder for the residents of these neighborhoods to improve their social standing [Nijman and Wei, 2020]. As a result, addressing spatial inequalities and promoting equitable urban development becomes an essential aspect of creating more inclusive and sustainable cities. Thankfully, improving access across neighborhoods and supporting a more equal distribution of services can mend broken social networks and improve economic outcomes across the board [Toth et al., 2021]. This is of utmost importance since discrimination and employment networks may be more relevant than the raw presence of jobs in explaining racial gaps in employment [Galster and Sharkey, 2017].

The literature shows that cities, while offering immense opportunities, can also exacerbate inequalities if not adequately planned. Infrastructure development, and access to resources all play a significant role in shaping the lives of urban residents. Tackling these challenges to achieve a more equitable urban environment is crucial for the future sustainability of cities. Thankfully, the spatial distribution of inequalities can be overcome with appropriate transport infrastructure (Committee of the transport access manual [2020], Firth et al. [2021]).

2.2.2. The role of transport in tackling those inequalities

An important step towards creating more equal cities involves improving their transit infrastructure [Calderón and Servén, 2014], which not only mitigates the effects of income inequalities [Bittencourt and Giannotti, 2021] but also enhances social mobility by providing better access to opportunities [Nieuwenhuis et al., 2020]. However, it's worth noting that transport infrastructure can also contribute to the inequalities mentioned earlier. Inequality in transport provision also results in low-income individuals traveling at lower speeds and covering smaller distances than their high-income counterparts [Cui et al., 2019], and mobility opportunities tend to be unevenly distributed among different social groups and across the city's space [Miciukiewicz and Vigar, 2012].

The structural and overlapping inequalities in society and cities result in, and are reinforced by, uneven levels of access to opportunities [Bittencourt and Giannotti, 2021]. When examining access to healthcare in three large cities in Cascadia, Mayaud et al. [2019] revealed that lower-income citizens, even if they live closer to healthcare facilities than their high-income counterparts, have lower accessibility to said healthcare due to proportionally higher transportation costs. Such disparities can lead to significant barriers for marginalized communities, limiting their access to essential services and economic opportunities.

Bicycle infrastructure is not immune to these criticisms, as its developments tend to be unequal in their distribution of benefits. For example, a study conducted in 22 cities in the US reveals that neighborhoods with lower educational attainment and a higher proportion of Latino residents had lower access to bicycle lanes [Braun et al., 2019]. In addition, a study conducted in Vancouver, Canada, shows that "Chinese people, children, and populations with lower education levels" face inequities in access to bicycle infrastructure [Firth et al., 2021]. It has further been suggested that bicycle infrastructure has led to gentrification in the US [Hirsch et al., 2017], which displaces low-income residents, further perpetuating social and economic disparities.

Clearly, bicycle infrastructure must be developed carefully with a clear understanding of the inequalities it may perpetuate,

2.3. Introducing Equity

As was established in section 2.1, inequalities are rampant in urban spaces, and specific action needs to be taken in order to combat them. This means that the availability of opportunities to all citizens does not lead to all citizens having equal opportunities. Introducing the concept of equity, or the fair distribution of benefits and costs among members of society [Di Ciommo and Shiftan, 2017, Litman, 2002], thus becomes necessary.

2.3.1. Defining equity

Equity is a moral judgment based on what is considered “fair” [Camporeale et al., 2017]. However, defining what is fair is difficult due to the existence of diverse social norms van Wee and Geurs [2011]. Equity can be divided into two broad categories: horizontal equity, which focuses on individuals with the same necessities, and vertical equity, which focuses on individuals with different needs. These two types of equity often overlap or conflict, and which one to prioritize is context-dependent [Litman, 2002].

Selecting a moral principle at the beginning of a study allows for distributional consequences to be considered [Jafino, 2021]. The chosen moral principle defines what is fair and can be based on different theories of justice.

2.3.2. Theories of Justice

The three most common theories of justice in transport equity literature are egalitarianism, utilitarianism, and Rawlsianism [Sun and Zacharias, 2020].

Egalitarianism implies that every user of the system should get the same benefit from it as all other users [Litman, 2002]. This approach wrongfully assumes that everyone has the same needs, leading to citizens with more privilege gaining the same utility as those without privilege, reinforcing inequalities [Pereira et al., 2017].

Utilitarianism shifts the focus from the individual to the entire group and attempts to produce the greatest good. It is the philosophical basis of Cost-Benefit-Analysis [Pereira et al., 2017], a popular policy-making tool that will be discussed in detail later. Achieving the greatest good is prioritized over consideration of the distribution of positive and negative outcomes, making utilitarianism face the same criticisms as egalitarianism [Martens et al., 2012].

Rawls’ egalitarianism aims to avoid egalitarianism’s and utilitarianism’s tendency to exacerbate inequalities. In Rawls’ view, the distribution of “primary social goods”, which can be the accessibility of opportunities[Pereira et al., 2017], should always be improved in a way that favors the least well-off [Rawls, 1971]. This shifts the focus away from the whole group (utilitarianism) back to individuals (egalitarianism) but considers individuals’ starting points, needs, and circumstances when deciding what is fair (Rawls’ addition).

2.3.3. Introducing equity in transport policy

As mentioned above, Cost-Benefit-Analysis (CBA) is the most widely used method for the evaluation of transport projects [Di Ciommo and Shiftan, 2017], quantifying positive and negative consequences of a project in monetary terms. Since CBA is based on utilitarianism, it can lead to seemingly great projects being hurtful to certain populations. As long as the overall utility of the project is greater than that of its alternatives, it does not matter who profits and who doesn't. However, the quantification methods employed may be biased towards higher-income citizens Di Ciommo and Shiftan [2017], Lucas et al. [2016], van Wee and Geurs [2011], meaning that projects serving privileged groups may be favored over others.

When focusing on transport projects, equity is introduced using the concept of accessibility [Lucas et al., 2016, Sun and Zacharias, 2020, Pereira et al., 2017, Curl, 2018, Cui et al., 2019, Committee of the transport access manual, 2020, Deboosere and El-Geneidy, 2018]. Different definitions of accessibility revolve around the concept of the ease with which key destinations can be accessed, based on travel times to better reflect how citizens plan their mobility [Cui et al., 2019].

Focusing on accessibility requires determining which populations to prioritize and what their needs are [van Wee and Geurs, 2011]. Most transport poverty literature mentions low-income citizens as the most vulnerable population, but other vulnerable populations include ethnic minorities, women, unemployed people, people with low educational attainment, and disabled people [van Wee and Geurs, 2011, Simcock et al., 2021, Lucas and Jones, 2012, Litman, 2002, Nicoletti et al., 2022]. Their most important trips are usually their commute to school or work van Wee and Mouter [2021].

Improving accessibility requires understanding which parts of the transport system are most relevant to which populations, a process that can be supported through network criticality analysis. It identifies which segments are important in a transport network, resulting in a ranking of each segment depending on its importance to the system for each population of interest [Jafino, 2021, Yap et al., 2021]. Conducting such an analysis without differentiating between populations implies a utilitarian approach, favoring the masses and linking back to CBA.

2.4. Conclusion, Knowledge Gap and Research Questions

In Section 2.1, we established that developing bicycle infrastructure is a promising way to reduce GHG emissions, but only if it's developed to support commuting trips. In Section 2.2, we warned that poorly planned bicycle infrastructure could perpetuate or even worsen urban inequalities, which are complex, multi-faceted, and often compounding. In Section 3, we presented a few ways to introduce equity into transport planning, inspired by the conclusions from Sections 1 and 2. Although research is well-established in each specific domain presented, there is little research on how bicycle infrastructure can be developed to reduce GHG emissions while also considering the equitable distribution of benefits by, at the very least, not contributing to urban inequalities. This presents a knowledge gap that will be addressed in this project through the following research question and subquestions (SQs):

"How does including equity in transport planning change the development of the bicycle infrastructure?"

- *SQ1: How can bicycle lanes that serve both for the reduction of GHG emissions and for the reduction of inequalities be conceptualized?*
- *SQ2: How would the bicycle infrastructure of a city develop without equity considerations?*
- *SQ3: How would the bicycle infrastructure of a city develop under different scenarios where equity is explicitly added to the current considerations?*

These questions illustrate the approach taken in this research.

3. Research Approach

This chapter describes the research approach as established by the research questions defined in the previous chapter. It begins by tying the subquestions together and then dives into the overarching approach to the model development.

3.1. Overall approach of this research

The overall approach taken in this research is illustrated by the research question and subquestions defined at the end of the previous chapter. We first explain how all subquestions will be answered individually and proceed to tie them together to answer the main research question.

SQ1: The first subquestion aims to identify the characteristics of bicycle infrastructure that serves the current trend of reducing GHG emissions and then expands these characteristics with those of a bicycle infrastructure that allows for the introduction of equity considerations. A bicycle lane that complies with all of these requirements is expected to help reduce both GHG emissions and urban transport inequalities.

SQ2: The second subquestion will guide the development of a model (explained in the next section) in which possible bicycle infrastructure additions can be weighted against each other depending on the benefit they provide according to utilitarian thinking, the current default in policy-making as explained in the previous section. The outcome of this part of the research is a ranked list of possible additions to the current bicycle infrastructure according to utilitarian thinking.

SQ3: The third and last subquestion will lead to the expansion of the model developed previously to include equity considerations in the weighing of possible additions to bicycle infrastructure. The outcome of this part of the research is an equity-weighted ranked list of possible additions to the current bicycle infrastructure.

The main research question will then be answered by comparing the results of *SQ2* and *SQ3*, which are based on a model whose conceptualization is guided by the findings of *SQ1*. The differences in outcomes for *SQ2* and *SQ3* will illustrate the trade-offs that must be navigated by decision-makers when balancing multiple considerations into the planning of new transport infrastructure.

3.2. Modeling approach

Answering *SQ2* and *SQ3* requires the development of a transport model, where possible developments of the bicycle infrastructure can be weighted against each other. We will follow an approach that will combine that of Vybornova et al. [2022] and Yap et al. [2021].

The model will be based on Vybornova et al. [2022]'s work, following the so-called IPDC procedure. It stands for Identify, Prioritise, Decluster, and Classify. They develop a model where bicycle lanes can only be developed along the existing road network and connect already-existing pieces of infrastructure. This is referred to as "closing a gap" and constitutes the "Identify" step. The prioritization step calculates a benefit metric for the closing of each gap, leading to a ranking and allowing the comparison of different infrastructure expansion projects based on their expected benefit. Since gaps may be closed in different ways, different closing possibilities may majorly overlap and are thus declustered in the third step. Although Vybornova et al. [2022] finish by classifying what each gap is, for example, a bridge or an intersection, we will stop after the declustering step, since only the ranking of the remaining gaps is of interest to our research. This is our first major modification to the approach.

Our second and last major modification to the approach is the change in the calculation of the benefit metric. Vybornova et al. [2022] base their closing benefit metric on network characteristics of each link, a measure that does not allow to choose which trips are considered or which populations to prioritize. In order to ensure that the added bicycle lanes follow the characteristics defined in *SQ1* and that equity can be included when deciding which gaps to close for *SQ3*, the benefit metric will be modified to follow the approach of Yap et al. [2021]. They determine the trip demand between administrative output areas based on the local populations' socio-economic characteristics, which is then used to assign traffic to each link of the network. This traffic can be used as a replacement of the network characteristics of each link used by Vybornova et al. [2022]. Yap et al. [2021]'s definition of demand can be expanded to prioritize specific populations but is usable as a utilitarian approach without the expansion, allowing for a meaningful comparison of results from *SQ2* and *SQ3*.

Figure 3.1 summarizes the approach described above. In short, we use geographical data to determine how many trips take place between different neighborhoods, leading to a utilitarian ranking of infrastructure projects. We then add socio-economic data to the geographical data to rank projects based on fairness, using the same logic as before.

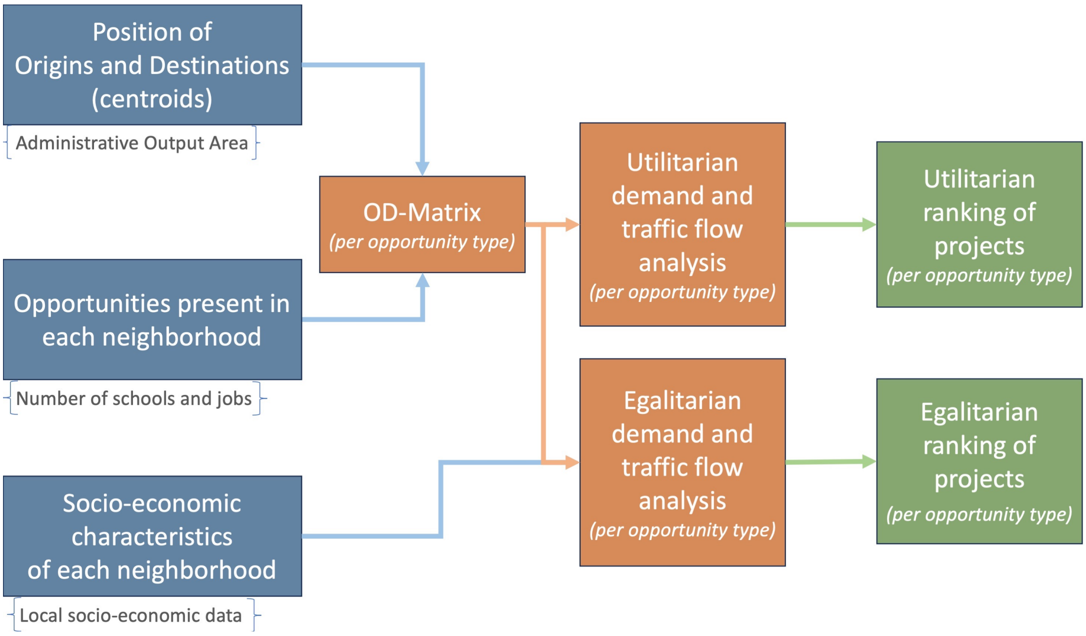

Figure 3.1.: The approach used in this research to rank infrastructure projects based on Yap et al. [2021]. Blue boxes relate to the conceptualization of the model with an indication of the required data in brackets underneath, orange boxes are calculation steps done within the model, and the green boxes are the desired output. The comparison of these outputs is expected to reveal trade-offs.

4. Methods

This chapter begins with a description of the chosen case study, followed by the conceptualization of the perfect bicycle lane achieving both environmentally and socially sustainable goals, answering *SQ1*. The model created in this study is then presented, followed by the development of the equity-weighted benefit metric. The chapter concludes with the experimental setup applied to the model, which will be used to answer *SQ2* and *SQ3*.

4.1. Case study: the Grand Paris Metropolis (GPM)

The Grand Paris Metropolis is a current project of the city of Paris and its surrounding suburbs to coordinate urban development endeavors and slowly merge into one [Government, 2015]. Some steps towards unity have been taken for example by homogenizing the cost of public transport over the area [STIF, 2015], but the development of bicycle lanes is still a very local process, with all 133 municipalities within the Metropolis developing their own plans.

The city of Paris, not the Grand Paris Metropolis, has set the goal of becoming one of the most bicycle-friendly cities in Europe [Pechin, 2021], a goal that is being achieved by closing major roads within the city and turning them into bicycle lanes. This can be expected to reduce air and noise pollution within the city as well as promote healthier lifestyles for locals as explained in the previous chapter, and ridership has already increased by 54% since the setting of this goal [Transport and Environment, 2020].

Sadly, this incredible progress is not being mirrored outside of the city, and there are currently no plans to better public transport service or parking infrastructure at the edge of the city for those that live too far out to cycle all the way into the city. Since the inner city is much more expensive to live in than the outskirts, the current planning of cycling infrastructure inadvertently spreads its benefits and negative externalities unfairly, privileging the already-privileged population of inner Paris and making the already-long commute of citizens from the outskirts, who are likely less well-off, more difficult.

It is this junction between the quick development of cycling infrastructure and the potentially unfair distribution of externalities that lends the Metropolis to this study.

4.2. Conceptualizing the perfect bicycle lane

Chapter 2 shed light on the specific characteristics of bicycle infrastructure needed to ensure that it leads to the desired outcomes.

In order to support the reduction of GHG emissions, Section 2.1 showed that it is important for bicycle trips to *replace* car trips. This means that bicycle infrastructure used for recreational purposes is not conducive to this goal, despite having a host of other benefits. A common car trip that can be easily replaced by a bicycle trip is the commute. It is also important to ensure that the bicycle infrastructure will be used, meaning that it must be coherent (well-connected) and safe (segregated from traffic).

In order to support the reduction of inequalities, Section 2.4 showed that it is important to focus on vulnerable populations and their needs (Rawls' egalitarianism) instead of looking at the population as a whole (utilitarianism). Bicycle infrastructure can thus only support the reduction of inequalities if it is specifically developed with vulnerable populations in mind. This is somewhat at odds with the paragraph above since focusing on subsets of the population could lead to infrastructure that is used by fewer citizens, meaning fewer car trips are replaced. This conflict between both goals may lead to different outcomes in the development of the infrastructure, which will become visible in the experiments conducted in this study. Since the focus will be placed on commuting trips to ensure that the bicycle infrastructure can help reduce GHG emissions, the vulnerable populations to consider are those that most need access to the relevant destination. Vulnerable adults in this study will be those living in neighborhoods with low median incomes, since they may be the ones who need access to work the most. Vulnerable children in this study will be those living in neighborhoods with low education levels, since they may be the ones who need access to school the most. These vulnerable populations are often mentioned in transport poverty literature, as mentioned in the previous Chapter.

To summarize, the bicycle lane that can both combat GHG emissions and inequalities has the following characteristics:

- It is used to *commute*, i.e used by adults going to work or children going to school
- It is *safe*, meaning that it is segregated from car traffic
- It is *coherent*, meaning that its quality does not vary much over the network and that trips can be completed without having to mix with car traffic at any point
- It *focuses on vulnerable populations*, meaning that it is focused on adults from areas with low median income and children from areas with low educational levels in the context of commuting.

4.3. Model conceptualization

The model's goal is to allow the realistic simulation of commuting trips between different areas of a city, with the aim of finding out which gaps in the bicycle infrastructure are the most important to close depending on which subpopulation's trips are prioritized. Closing gaps in the infrastructure will ensure that the final infrastructure is coherent, while focusing on commuting trips will help ensure that car trips are replaced by bicycle trips.

To this aim, the model needs to accurately represent the street network of the city with information regarding the existence and quality of the bicycle infrastructure, as well as provide information on the population and the number of Points of Interest (POIs) present in each administrative output area. This information will ensure that the bicycle infrastructure is safe, that it can be used for commuting purposes and that it can be geared towards vulnerable populations and their commuting desitnations if desired.

4.3.1. The street network

The conceptualization of this part of the model is taken from Vybornova et al. [2022]'s work, which automates the detection of bicycle gaps in Copenhagen and ranks those gaps by importance based on their estimated use.

A link in the road network, which represents a road segment, is considered bicycle-friendly if a bicycle lane is present and completely separated from the car traffic. If such a lane is not present, the link is considered car-friendly. Once the streets have been classified as either bicycle- or car-friendly, the network is modified so that nodes exclusively represent road intersections, and links exclusively represent road segments between these intersections. The simplification process is part of the data cleaning process and is explained in Appendix A, illustrated in Figure 4.1. This procedure does not lead to any loss of information regarding the street network.

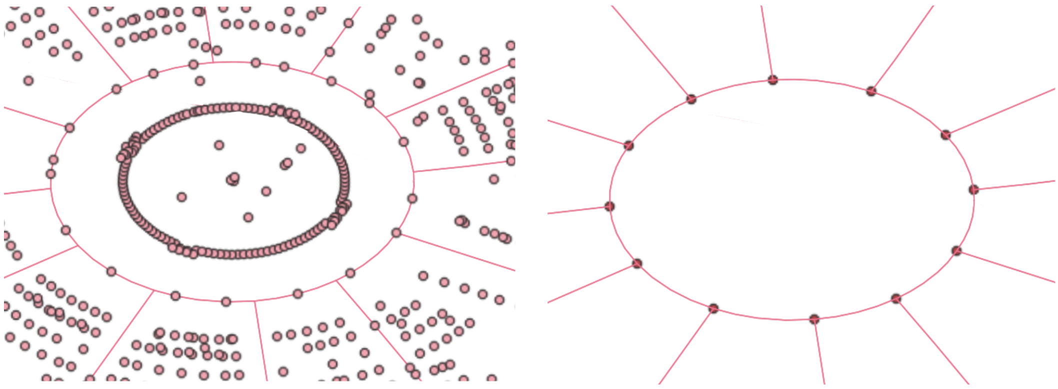

Figure 4.1.: Illustration of the network simplification procedure. The network as taken from Open Street Maps (left) is modified so that street intersections become nodes and street segments between intersections become links. The resulting network (right) is better adapted to the purpose of this research.

Once the street network fits the desired format, the nodes, which represent street intersections, can be classified as ”bicycle nodes”, meaning they are only connected to bicycle-friendly links, as ”car nodes”, meaning they are only connected to car-friendly links, or as ”contact nodes”, meaning they are connected to both bicycle-friendly and car-friendly links. This leads to a network like the one created by Vybornova et al. [2022] for the city of Copenhagen. In such a network, it is easy to define a ”gap” in bicycle infrastructure as the shortest path between a pair of contact nodes consisting only of car-friendly links, as shown in Figure 4.2. Building protected bicycle lanes along this path would lead to an uninterrupted piece of bicycle infrastructure linking two pieces of already-existing bicycle infrastructure, thus closing the ”gap” between them.

The implementation of the model is done in Python. The street network of the area is taken from OpenStreetMaps (OSM) [Open Street Maps, 2022], an open data source, using the OSMnx library [Boeing, 2017]. The network is then translated into a NetworkX graph using the eponymous library [Hagberg et al., 2008] as well as the GeoPandas library [Jordahl et al., 2020]. The road segments are classified as either bicycle-friendly (called a ”bicycle link”) or non-bicycle-friendly (called a ”car-link”) depending on their OSM tags, which are keywords used by OSM to describe different characteristics of the street segments. The comprehensive list of tags used for the classification of links is presented with the data cleaning process in Appendix A.

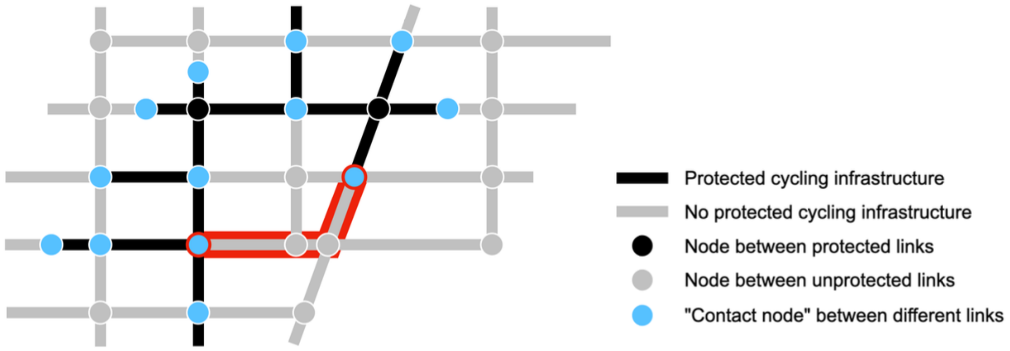

Figure 4.2.: Schematic representation of different link and node definitions, as well as that of a gap (in red). A gap is a shortest path consisting only of unprotected links connecting two contact nodes. Retrieved from Vybornova et al. [2022]

4.3.2. The Administrative Output Areas

Although the street network is represented at a high level of detail, socio-economic data is not available at such a granular level because it would allow the identification of individuals and thus raise privacy concerns. This means that trips cannot begin or end at specific addresses or POIs. Instead, they will be modeled as beginning and ending at the center of the smallest administrative output areas available. This layer of the model only consists of nodes, namely the centroids of each administrative output area, and each centroid node contains all socio-economic and POI information needed for this research as its attributes, which are described in detail later. These attributes are used as an indication of the socio-economic situation of the different administrative output areas and of how many opportunities of different kinds are available in them.

In France, the smallest administrative output area available is an area of roughly 4000 inhabitants, called an IRIS. In the context of this research, only ”habitat” IRISs are considered, since no socio-economic data is available on residents of ”industrial” or ”commercial” areas. An overview of the habitat IRISs present in the Grand Paris Metropolis is presented in Figure 4.3. The areas without a ”habitat” IRIS are usually forests, fields, industrial areas, hospitals, and other similarly out-of-scope areas.

The attributes of interest to this research were defined as follows for the IRISs of GPM:

1. IRIS code, used for reference in the results
2. Active population density (citizens between the ages of 18 and 64)
3. School-aged population density (citizens between the ages of 5 and 15)
4. Median income
5. Education level, defined as one minus the proportion of unschooled citizens above the age of 15 without any diplomas
6. The number of schools
7. The number of people employed in the IRIS regardless of their place of residence.

The data used, its sources, and its cleaning process are described in Appendix A.

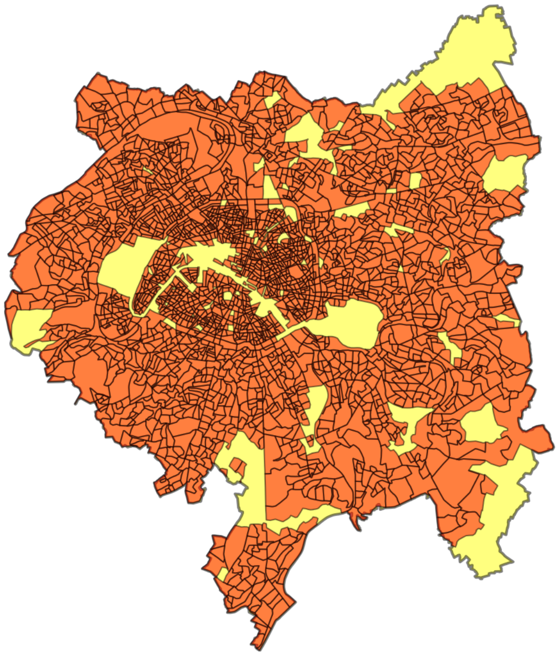

Figure 4.3.: Grand Paris Metropolis (yellow background) and its administrative output areas known as IRIS (orange). The areas without an IRIS are usually forests, fields, industry, hospital complexes, airports, etc.

4.3.3. Connecting both layers

Since centroids don't always coincide with the existing street network, additional bicycle-friendly street segments need to be created to connect the centroids with the closest node or edge of the street network. Classifying these imaginary segments as bicycle-friendly ensures that they don't influence the prioritization of gaps in the infrastructure. If the centroid is connected to a road segment (a link in the street network), that segment is broken up at its intersection with the new road segment, and a new node is created to describe said intersection. If the centroid is connected to an already-existing road intersection (i.e. a node of the street network), the node type is modified if needed to accommodate its new connection to a bicycle-friendly road. This procedure is implemented using the SnKit library in Python.

4.4. Defining the Importance of a Gap

Once the model layers have been created and connected, ranking infrastructure gaps requires estimating the traffic flow on each gap as well as defining a closure benefit metric on which to compare gaps.

4.4.1. Estimating traffic flow

The unit of travel is the "trip", or one person/vehicle traveling from one origin to one destination without intermediate stops, and trips are commonly separated by purpose [National Academies of Sciences, Engineering, and Medicine, 2012]. We divide this process into two steps:

- *Trip demand*: The number of trips between each origin and each destination is estimated in the form of an Origin-Destination (OD) matrix. These matrices have all origins as their rows, all destinations as their columns, and the element of row i and column j denotes the number of trips from origin i to destination j. In our model, each origin and destination is an IRIS centroid.
- *Trip assignment*: The number of trips between two points on the map determined in the previous step is turned into a traffic flow on each street link of the network.

Trip demand

Many state-of-the-art population mobility models fall under two traditions [Camargo et al., 2019]): gravity-based models dating back to Zipf (1947) and intervening opportunities models, such as Stouffer [1940]'s, extended by Simini et al. [2012]. If the reader chooses to explore Stouffer's work, they should be warned of the outdated language used.

In gravity models, the key assumption is that trip volume between locations decreases as the distance between origin and destination increases. They utilize impedance functions to discount opportunities based on travel distance, time, or cost, and these functions vary in form, though often resembling exponential or power-law functions [Committee of the transport access manual, 2020].

Intervening opportunity models associate trip volume with the number of destinations between two places. Stouffer [1940]'s original intervening opportunities model posits that "The number of persons going a given distance is directly proportional to the number of opportunities at that distance and inversely proportional to the number of intervening opportunities". Intervening opportunities describe any opportunity that the individual may encounter on their way to their original destination.

Lenormand et al. [2016] highlight the difficulty in picking between radiation and gravity models, as it often depends on input data and purposes. Given each model's strengths and limitations, the choice should align with the research's specific objectives. In their comparison of gravity and intervening opportunities models, Lenormand et al. [2016] estimate that the former were better adapted to predicting commuting behavior, which is why we choose this method for our research.

Travel assignment

Once the OD matrix has been created, the specificities of how each trip is expected to take place, i.e. which itinerary it will follow, is determined. The easiest, most straightforward way of assigning traffic is to assume that all travelers will follow the shortest path linking their origin and their destination, be it in time or in distance units, as is done in Yap et al. [2021]'s work, which we will take inspiration from. It could also be done using simple network metrics like betweenness centrality, which calculates how many shortest paths include a specific link of the network, as done inVybornova et al. [2022]'s work. However, that method does not use an OD matrix and thus does not differentiate between populations or trip types.

4.4.2. Defining a new closure benefit metric B

Vybornova et al. [2022] defines a closure benefit metric to prioritize bicycle infrastructure gaps. This closure benefit metric revolves around the estimated traffic flow on the link, for which the betweenness centrality is used as a proxy. This assumes that exactly one trip is taken between each possible pair of nodes. However, their approach is not suitable for our study because it considers all possible trips on the network, their method excludes long trips, and there is no possibility to differentiate between different populations. We only focus on commuting trips between specific points (IRIS centroids), we want to prioritize certain populations, and we don't want to assume a maximum trip length. Yap et al. [2021]'s work offers a promising alternative, using a gravitational model and considering trips between centroids of administrative output areas regardless of trip length.

For reference, Vybornova et al. [2022] define the absolute benefit metric $\mathbf{B}^*_\lambda(\mathbf{g})$ of closing a gap $\mathbf{g}$ as follows:

$$\mathbf{B}^*_\lambda(\mathbf{g}) = \sum_{l \in \mathbf{g}} c_\lambda(l) \cdot L(l), \tag{4.1}$$

where l represents each link of gap $\mathbf{g}$, $c_\lambda(l)$ is the betweenness centrality of link l, used as traffic flow, and L is the length of link l. The index λ denotes the maximum length of trips considered. In order to account for the cost-efficiency of closing gaps, the final benefit of closing a gap is Equation 4.1 divided by the total length of gap $\mathbf{g}$.

Determining demand without equity

Gravitational models define a production potential for each origin, which represents how many trips can be expected to begin from that area, and an attraction potential for each destination, which represents how likely it is for a trip to end at that specific destination. Usually, the population density of each area is used as its production and attraction potential, as done in Yap et al. [2021] on the scale of a country. At a smaller scale like that of a city, however, it is recommended to use the number of POIs at the destination as its attraction potential instead of the population density [Camargo et al., 2019]. Once these potentials are defined, they are scaled with a deterrence factor representing how shorter trips are preferred to longer ones. It is common practice to use an exponential decay function.

Yap et al. [2021] define the demand for a trip between the centroids of two administrative output areas as follows:

$$d_{ij} = Q_i \cdot X_j \cdot \exp^{-C_{ij}} \text{ , with } C_{ij} = \frac{c_{ij}}{\max\limits_{i,j \in OD} c_{ij}} \tag{4.2}$$

where Q_i is the production potential of the origin and X_j is the attraction potential of the destination, for which Yap et al. [2021] use the corresponding population densities. The deterrence factor is $\exp^{-C_{ij}}$, with C_{ij} being the length of the shortest trip between nodes i and j divided by the length of the longest possible shortest trip between any nodes i and j on the network. This is a typical gravity-based model of mobility.

We will use Equation 4.2 for the non-equity-weighted demand, but we will use different proxies for the production potential and the attraction potential: instead of using total population densities, we will use specific sub-population densities for Q_i and the number of relevant POIs for X_j. For example, when looking at commuting trips to school, it is the child population density at the origin and the number of schools at the destination that will be considered instead of the total population density at both the origin and the destination.

Now that the baseline equation has been defined, it is time to include equity considerations.

Introducing socio-economic factors into the demand

Using Equation 4.2 allows us to simulate trip demand on the network, but it does not consider socio-economic factors yet. Yap et al. [2021] extend Equation 4.2, defining a modified demand d^*_{ij} which considers socio-economic factors and yields Equation 4.3:

$$d^*_{ij} = d_{ij} \cdot \left(\frac{w_i}{\bar{w}}\right)^{-\delta} \cdot \left(\frac{w_j}{\bar{w}}\right)^{-\delta} \tag{4.3}$$

with d_{ij} as defined in Equation 4.2, w the socio-economic factor to define vulnerable populations at origin i and destination j, $\bar{w}$ the average of that factor over the entire network and δ a so-called inequality aversion factor. The higher the factor δ, the stronger the consideration of vulnerability. This modified demand is no longer accurate to the physical reality of the network since some trips are counted multiple times, but it allows us to decide which trips should be prioritized.

Equation 4.3 was designed to favor origins and destinations with lower values of w. For example, if w represents the GDP per capita of an area, then a trip between area i and area j will be prioritized if areas i and j both have low GDPs per capita. The same trip will not be discounted if both areas i and j have a high GDP per capita. This is not fully fitting for this research: trips between areas of contrasting socio-economic status are discounted and trips between areas of lower socio-economic status are prioritized. Since we want to focus on the people taking the trips, we will only consider the socio-economic variable of the population at the origin when aiming for equity. Vulnerable populations need to be prioritized regardless of where they choose to go, and prioritizing their access to areas with similar socio-economic status as their own is unlikely to increase their access to opportunities more than connecting them to areas that are socio-economically different. This yields the final equation used in our research to define the demand D^*_{ij} between IRIS centroids while focusing on the socio-economic factor w:

$$D^*_{ij} = d_{ij} \cdot \left(\frac{w_i}{\overline{w}}\right)^{-\delta} \tag{4.4}$$

Just like in Yap et al. [2021]'s work, we are not sure which value of δ is most appropriate, so all calculations are done using three different values for δ, namely 0.5, 1, and 1.5. Once the demand has been calculated for each Origin-Destination pair both with and without equity considerations, it can be used to assign a traffic flow to the network.

Assigning a traffic flow and ranking gaps

The demand defined in Equations 4.2 and 4.4 cannot be used to directly replace the betweenness centrality c_λ from Equation 4.1 because it does not describe the expected use of each specific link of the network; the demand must first be translated into a traffic flow on each link through a traffic assignment algorithm. Instead of using the Frank-Wolfe algorithm like Yap et al. [2021] or the betweenness centrality like Vybornova et al. [2022], we will use a modified betweenness centrality c_{mod}. All trips from i to j will be assigned to the shortest path between i and j. This results in the cumulative number of trips that traverse each link within the network, the modified betweenness centrality c_{mod}, which we refer to as traffic flow. Links that belong to multiple shortest routes will experience increased traffic flow, reflecting their higher utilization. This modified betweenness centrality c_{mod} is used to replace the betweenness centrality c_λ in Equation 4.1 and yields our modified absolute benefit metric $\mathbf{B'}^*(\mathbf{g})$:

$$\mathbf{B'}^*(\mathbf{g}) = \sum_{l \in \mathbf{g}} c_{mod}(l) \cdot L(l), \tag{4.5}$$

.

This benefit metric needs to be scaled by the length of the gap in order to make different-sized gaps comparable. This yields our final modified benefit metric $\mathbf{B'}(\mathbf{g})$:

$$\mathbf{B'}(\mathbf{g}) = \frac{\sum_{l \in \mathbf{g}} c_{mod}(l) \cdot L(l)}{\sum_{l \in \mathbf{g}} L(l)}, \tag{4.6}$$

Its unit is a number of trips, namely the ratio of meters biked by meter of gap. Once this final modified benefit of closing each gap $\mathbf{B'}$ according to each scenario is calculated using the newly computed modified betweenness centrality c_{mod} based on the demand of each scenario (Equations 4.2 or 4.4), the ranking of gaps is straightforward. Following Vybornova et al. [2022]'s method, overlapping gaps are declustered and sorted based on their benefit metric for each scenario, with higher benefit metrics indicating greater importance for the considered vulnerable population. Given the computational cost of declustering gaps, only the top 10000 gaps will be declustered. The declustering will yield multiple rankings of gaps, allowing for comparison and analysis.

4.5. Experimental Setup

In the scope of this study, based on the findings in 4.2, only commuting trips need to be considered. They are broadly divided into two categories: adults (ages 18-64) commuting to work, and children (ages 5-15) commuting to school. The demand for these trips is calculated using both the baseline defined in Equation 4.2 and the equity-weighted demand defined in Equation 4.4 with different inequality aversions δ. This is summarized in Table 4.1.

In both bases, the population density of interest and the POIs are adapted to the scenario at hand. This means that, in the scenario of adults commuting to work, only the adult population density (citizens aged 18-64) is considered at the origin and only the number of jobs available (with the number of people employed there as a proxy) is considered at the destination. In the scenario of children going to school, only the school-aged population density (children aged 5-15) is considered at the origin, and only the number of schools is considered at the destination. When adding equity considerations to each scenario, a relevant vulnerability characteristic is introduced. For adults, this is the median income in their area, and for children, this is the education level of their area. These populations are often mentioned as vulnerable in transport poverty literature as mentioned in Chapter 2.

Tables 4.2 and 4.3 summarize the variables and proxies used for each experimental setup, where the baseline omits the inequality aversion factor δ and the socio-economic factor w.

Comparing the results of the scenarios with and without equity considerations will lead to a clearer understanding of the evolution of bicycle infrastructure depending on the inclusion or exclusion of equity considerations, thus answering *SQ2* and *SQ3*.

Table 4.1.: Summary of the equations used in each scenario for both experiments

Scenario	**Equation**
Baseline demand	$d_{ij} = Q_i \cdot X_j \cdot \exp^{-C_{ij}}$, with $C_{ij} = \frac{c_{ij}}{\max\limits_{i,j \in OD} c_{ij}}$
Equity-weighted demand	$D^*_{ij} = d_{ij} \cdot \left(\frac{w_i}{\overline{w}}\right)^{-\delta}$, with $\delta \in \{0.5, 1, 1.5\}$

Table 4.2.: Experimental setup for adults commuting to work. The baseline omits the deterrence factor δ and the socio-economic variable w

Origin	Population Q_i	Adults Pop. dens. of citizens aged 18-64
Destination	POI X_j	Number of jobs Number of people employed in the IRIS
Deterrence factor	δ	$0.5, 1, 1.5$
Socio-economic variable	w	Median income

Table 4.3.: Experimental setup for children commuting to school. The baseline omits the deterrence factor δ and the socio-economic variable w

Origin	Population Q_i	Children Pop. dens. of citizens aged 5-15
Destination	POI X_j	Number of schools Number of buildings marked as ”school” in OSM with a name
Deterrence factor	δ	$0.5, 1, 1.5$
Socio-economic variable	w	Education level, defined as the inverse of the proportion of citizens out of school above the age of 15 without a diploma to all citizens above the age of 15

5. Results

This section presents the results from the experiments conducted with the methods presented in Chapter 4. We begin with an exploratory data analysis (EDA) and then analyze the results of each experiment separately.

5.1. Exploratory Data analysis (EDA)

An EDA includes the visual exploration of the data and can allow a deeper understanding of the city or of future findings. This section will mainly consist of visualizations of the geographical and numerical distributions of all socio-economic variables of relevance to both experiments.

Current state of the bicycle network

We begin by visualizing the current state of the bicycle network in the Grand Paris Metropolis. To this aim, both the road network and the current bicycle network are illustrated in Figure 5.1. It is clear that the bicycle network in GPM is very disconnected and sparse, except inside the city of Paris, where clear efforts have been made to improve the extent and connectivity of the bicycle network. A few long stretches of bicycle lanes can be seen joining the city of Paris with its southern suburbs. The northern suburbs have their own somewhat dense bicycle network, and all other suburbs show short and isolated bicycle lanes. According to the characteristics of the desirable bicycle lane from the previous section, the city of Paris is much farther ahead than the rest of the Metropolis in terms of bicycle infrastructure development due to the connectivity of its network.

5.1.1. Variables of Experiment 1: Active population density, number of jobs and median income

In this section, we analyze the geographical and numerical distribution of the variables relevant to the first experiment, namely that of adults commuting to school. These variables are the active population density (ages 18-64), the number of jobs, and the median income.

Active Population Density

The active population density does not show any unexpected patterns. It is highest inside the city and lower in the suburbs, meaning that a lot more IRISs have a low population density than a high one. The related figures are displayed in Appendix B.

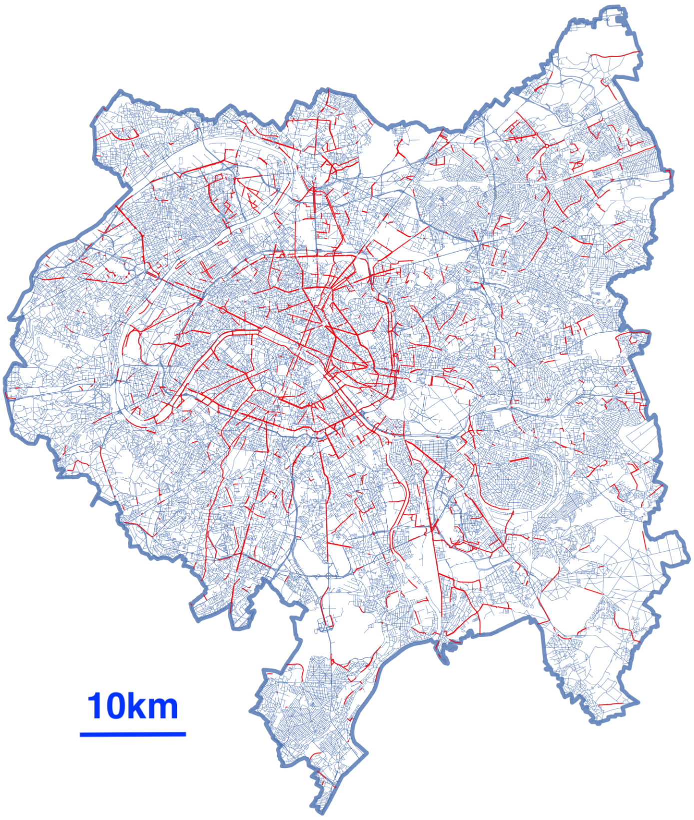

Figure 5.1.: Current road network (blue) and bicycle network (red) of the Grand Paris Metropolis

Number of Jobs

The number of jobs is displayed geographically in Figure 5.2 and numerically in Figure 5.3. The latter figure shows four clusters of values, discussed from the highest number of jobs to the lowest. The highest number of jobs is found in a few neighboring IRISs, namely those in the northwest quarter of the city of Paris. This area contains many of Paris' famous tourist attractions such as the Eiffel Tower, the Louvre Museum, the Garnier Opera, and the shopping district of the Champs-Elysees, where luxury companies have their French offices. Since Paris is one of the most visited cities in the world, the tourism industry generates many jobs. The isolated IRIS in the South with the second-highest number of jobs corresponds to Orly Airport and the Rungis market, the world's largest food market. The high job count may result from the disaggregation of commune-level values into IRIS-level ones, concentrating commune jobs in a small area due to neighboring IRISs not being classified as "habitable". The western suburbs of Paris, the third highest cluster in Figure 5.3, correspond to the La Défense business district. In comparison, the rest of the Metropolis displays much lower job availability, potentially linked to the absence of tourist attractions and related businesses.

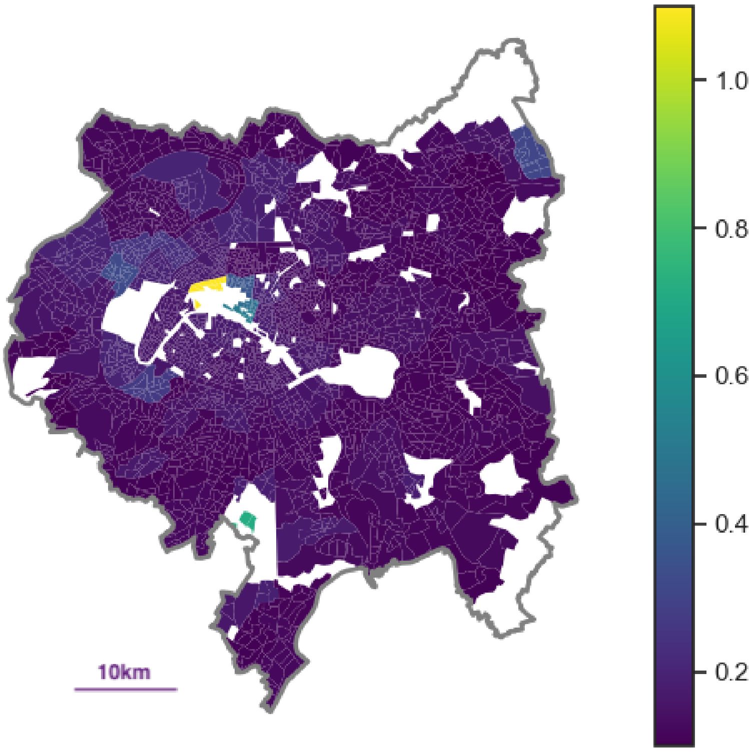

Figure 5.2.: Number of jobs in the Grand Paris Metropolis

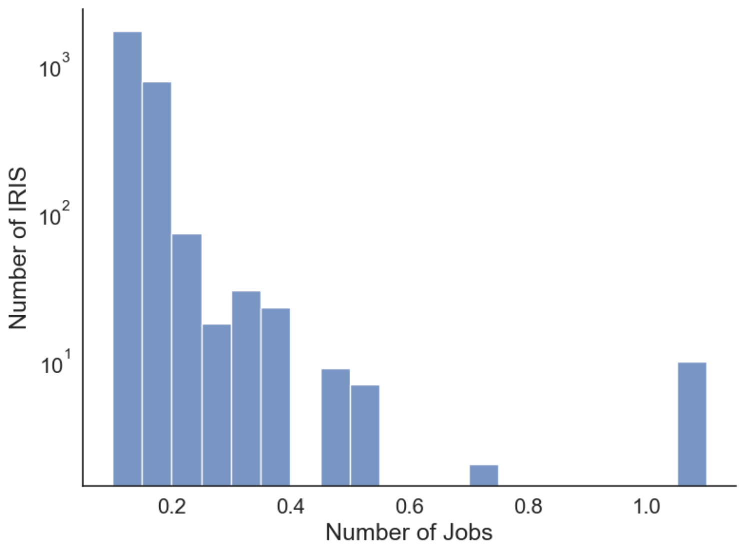

Figure 5.3.: Numerical distribution of the number of jobs in the Grand Paris Metropolis. Note the logarithmic scale of the y-axis.

Median Income

The median income is illustrated geographically in Figure 5.4 and numerically in Figure 5.5. Both figures display interesting characteristics. The median income is quite evenly distributed between its lowest and highest values, though very few IRISs contain the 3 highest median incomes, and it is geographically much less concentrated than the population density. However, some clear segregation lines are visible. The West of the Metropolis has the highest median-income neighborhoods, while the North and the South have the lowest median-income neighborhoods, and the transition from one to another is sometimes very abrupt. The high-income neighborhoods of the West partly overlap with the neighborhoods showing the highest number of jobs, indicating that the businesspeople of the district may live in the area.

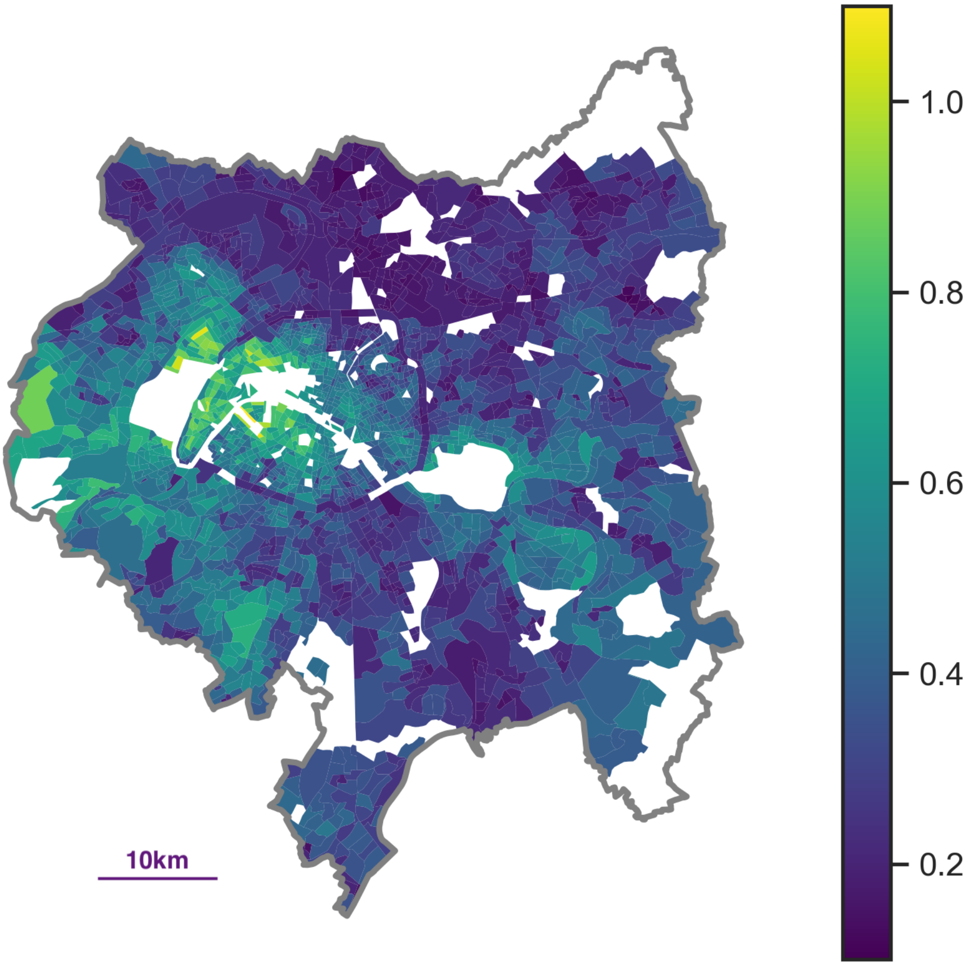

Figure 5.4.: Median income in the Grand Paris Metropolis

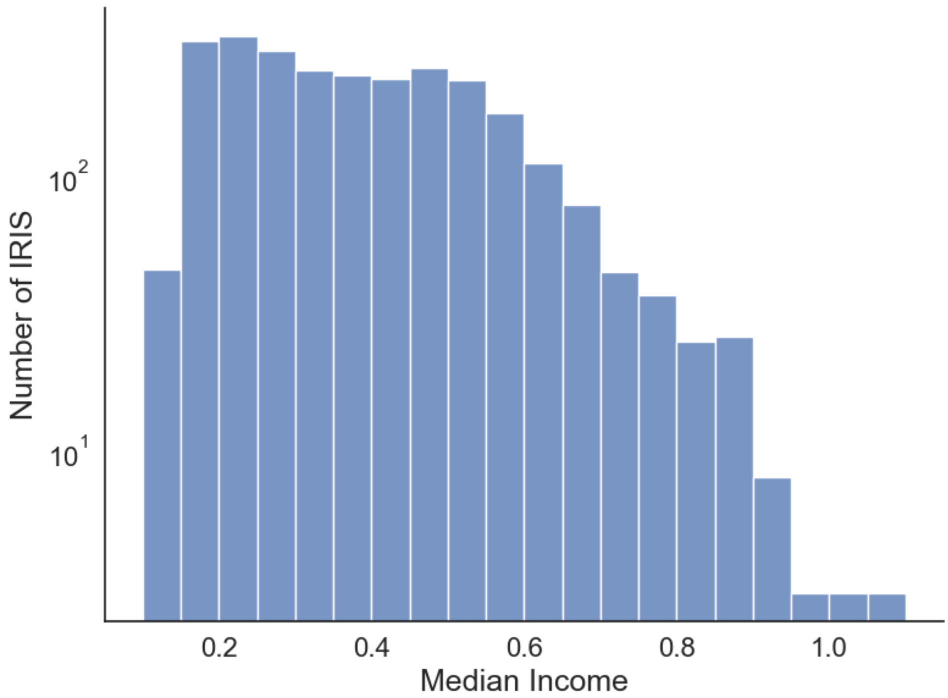

Figure 5.5.: Numerical Distribution of the Median Income in the Grand Paris Metropolis

5.1.2. Variables of Experiment 2: Child population density, number of schools and education level

In this section, we analyze the geographical and numerical distribution of the variables relevant to the second experiment, namely that of children commuting to school. These variables are the school population density (ages 5-15), the educational level, and the number of schools.

School Population Density

The school population density is very similar to the active population density. The related figures are displayed in Appendix B.

Number of Schools

As shown in Figure 5.6, most IRISs have few schools. However, as seen in Figure 5.7, IRISs with few schools are always close to IRISs with more schools, leading to an even distribution of schools over GPM and implying that no child needs to travel long distances to get a basic education.

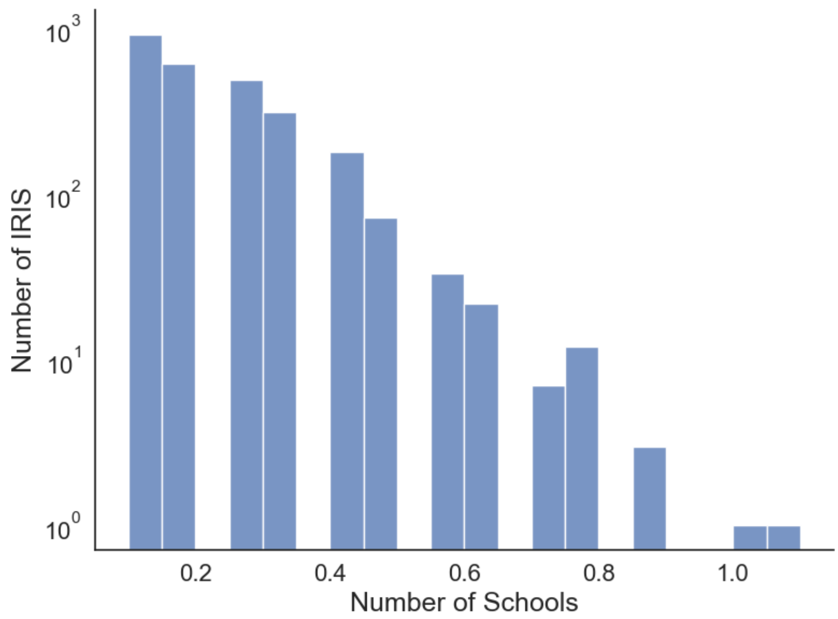

Figure 5.6.: Numerical distribution of the number of schools in the Grand Paris Metropolis

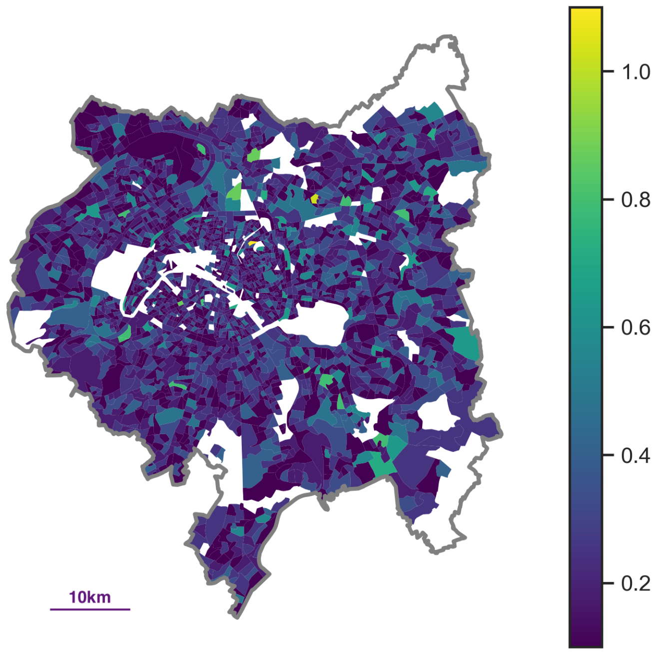

Figure 5.7.: Geographical distribution of the number of schools in the Grand Paris Metropolis

Education level

The education level is very high in most IRISs, as can be seen in Figure 5.8, which leads to a high average education level. This will lead to many neighborhoods being prioritized, which may limit the effect of said prioritization and reduce the magnitude of change caused by the introduction of equity. However, the geographical distribution of the education level shows that the western suburbs and the inner city have the highest concentration of high-education IRISs, while the northern and southern suburbs have the highest concentration of low-education IRISs. This geographical segregation of high- and low-education neighborhoods could help compensate for the effects of the high average education level since most of the prioritized neighborhoods will be concentrated within the northern and southern suburbs.

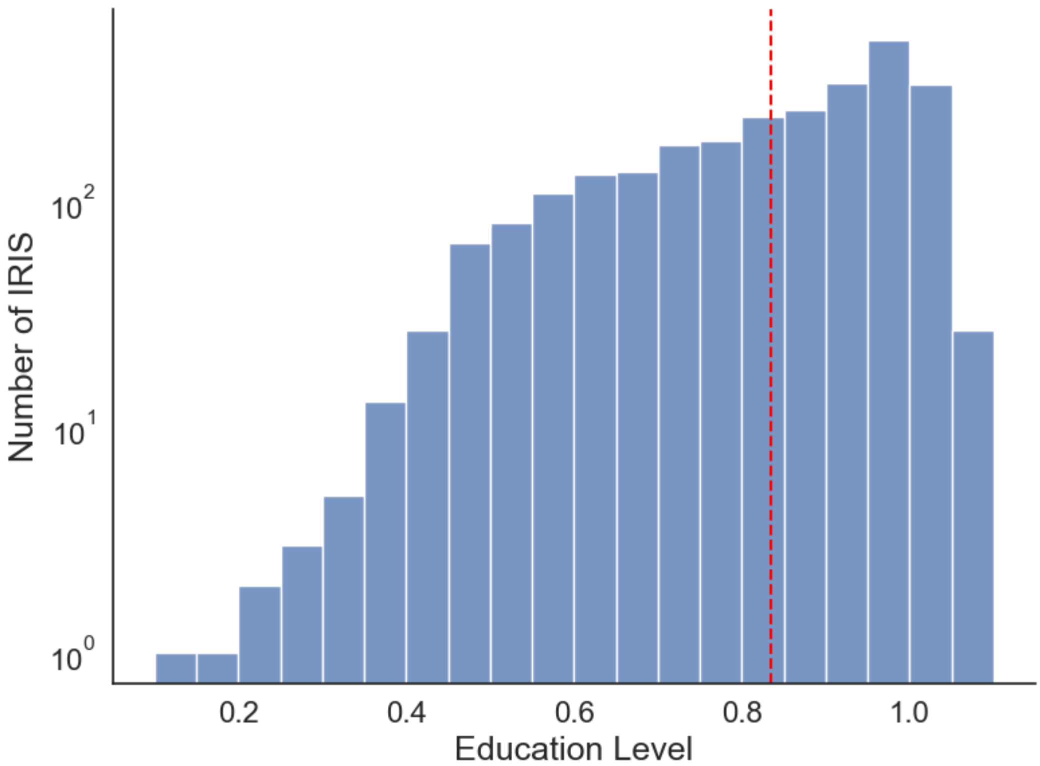

Figure 5.8.: Numerical distribution of the education level in the Grand Paris Metropolis with the mean value indicated by the red dotted line.

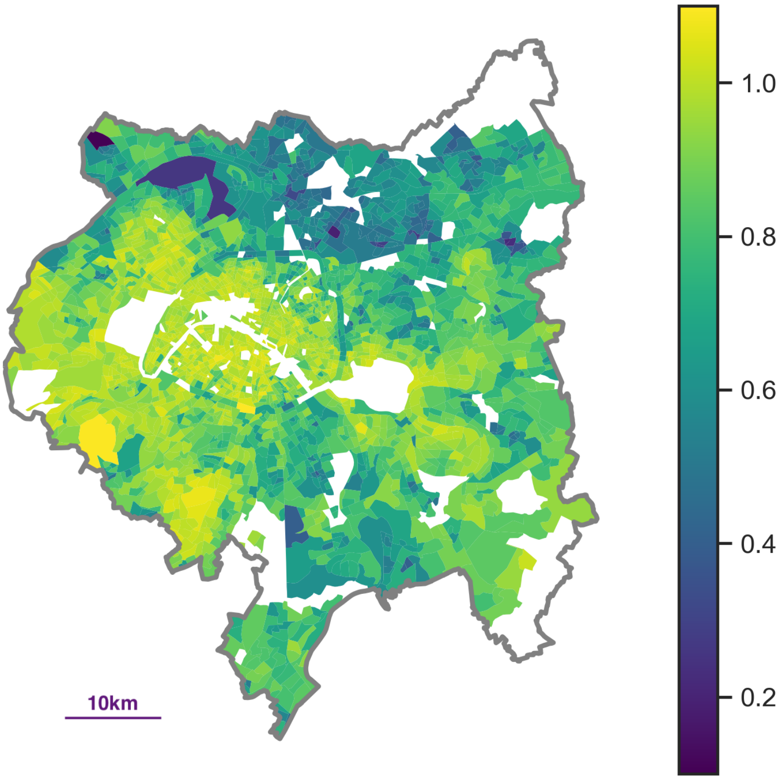

Figure 5.9.: Geographical distribution of the education level in the Grand Paris Metropolis.

5.2. Experiment 1: Adults commuting to work

After declustering the top 10000 gaps for each scenario of adults commuting to work, 255 gaps remain.

We begin by visualizing how the closing benefit metric varies over the remaining gaps to determine how many of them are relevant to this research. We then analyze them for any emerging patterns and changes when equity is introduced to different extents.

Evolution of the Closing Benefit Metric over the identified gaps

Not all remaining gaps are equally important to close, so we begin by visualizing the closing benefit metric of all remaining gaps in Figure 5.10 to determine how many need to be analyzed.

The closing benefit of gaps ranges from 0 to 1000000 and drops sharply with their ranking, especially at the extremities: the top and bottom 30 gaps see the sharpest decreases in closure benefit. The final closure benefit metric $\mathbf{B'(g)}$ represents the number of trips taken on a gap, so a sharp decrease in benefit implies a sharp decrease in usage of the gap. We thus only focus on the top 30 gaps and visualize their closure benefit more closely in Figure 5.11.

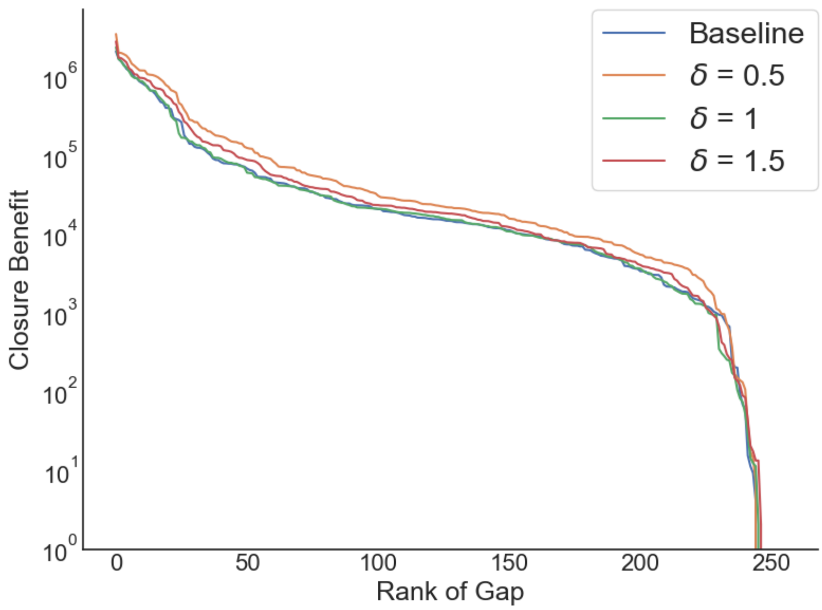

Figure 5.10.: Closure benefit of the remaining gaps after declustering for all scenarios of adults commuting to work. Note the logarithmic scale on the y-axis.

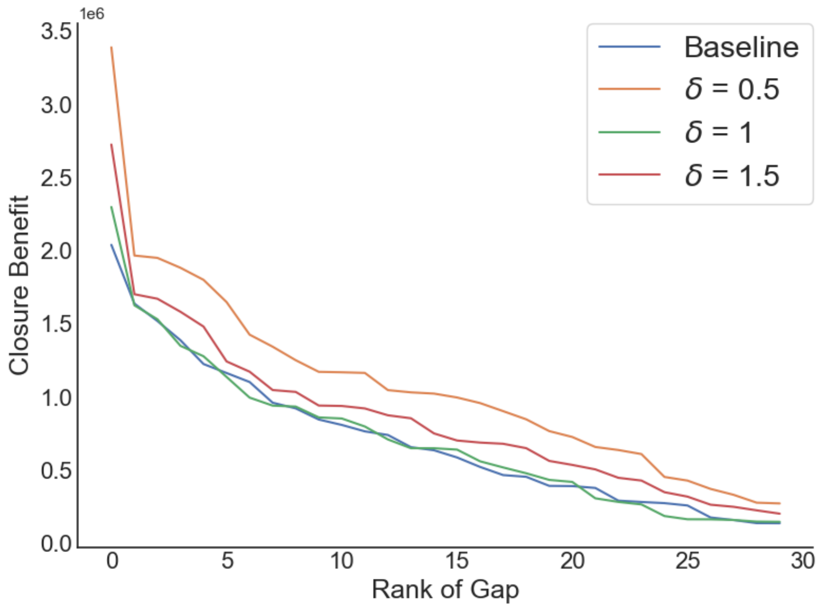

Figure 5.11.: Closure benefit of the top 30 gaps after declustering for all scenarios of adults commuting to work.

Analyzing commonalities of all scenarios

The top 30 gaps of all scenarios for the experiment of adults commuting to work are concentrated in the same area around the city of Paris as shown in Figure 5.12. All subsequent figures will focus on that area for clarity.

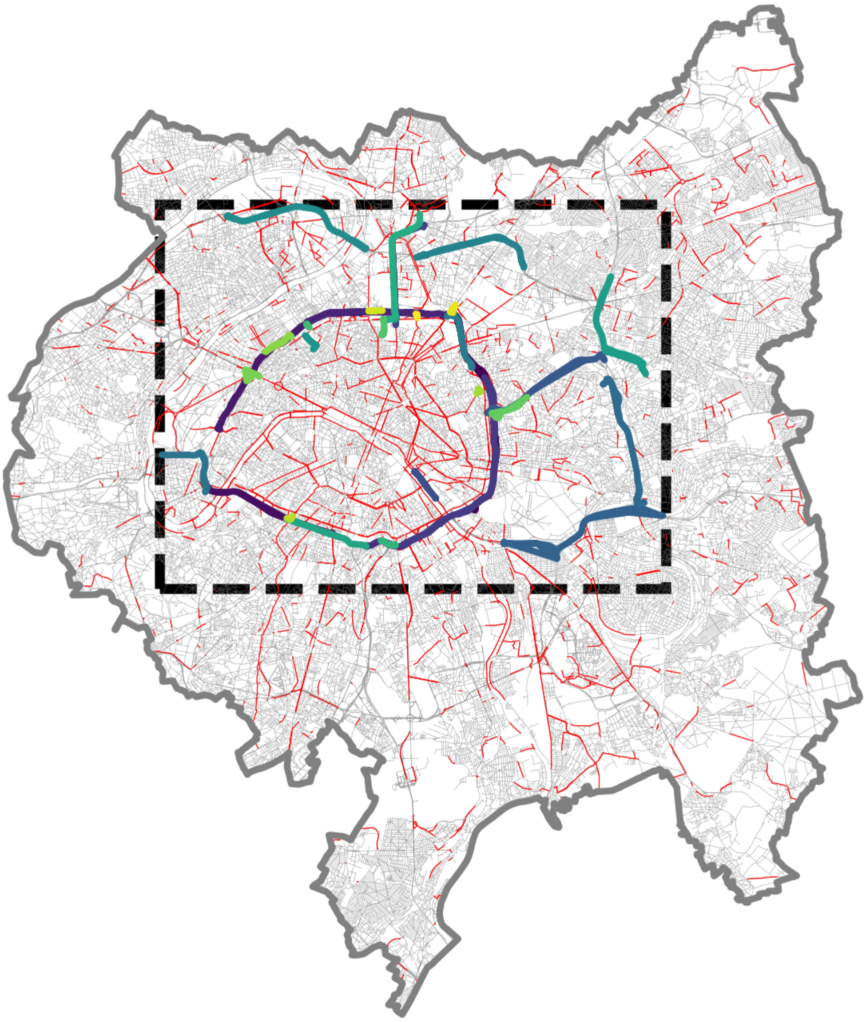

Figure 5.12.: The Grand Paris Metropolis with its road network (grey), its bicycle network (red), the top 30 gaps for the maximum equity scenario for reference (purple to yellow gradient), and the area that contains all top 30 gaps regardless of the scenario (dashed rectangle).

Some patterns emerge in how the top 30 gaps are placed in all scenarios and are visible in Figure 5.13, where the top 30 gaps for the baseline scenario are displayed. The most important gaps follow the limit of inner Paris along the Boulevard Périphérique, a very important ring road around the city. This road is likely being prioritized by the algorithm due to its capacity to quicken travel between areas on opposite sides of Paris. The next gaps in terms of importance tend to be long stretches of road linking primarily northern and eastern suburbs to this ring road, and the least important ones in the top 30 tend to be a piece of a bigger, more important gap on the Boulevard Périphérique. This hints at the fact that, although bigger pieces of infrastructure are more important to the coherence of the network, smaller parts can be prioritized and closed first if the bigger project is done in phases. It is also important to note that a few gaps are inside of the city, but they tend to link towards the ring road, indicating that the inside of the city of Paris has already developed a significantly better bicycle network than its surrounding areas.

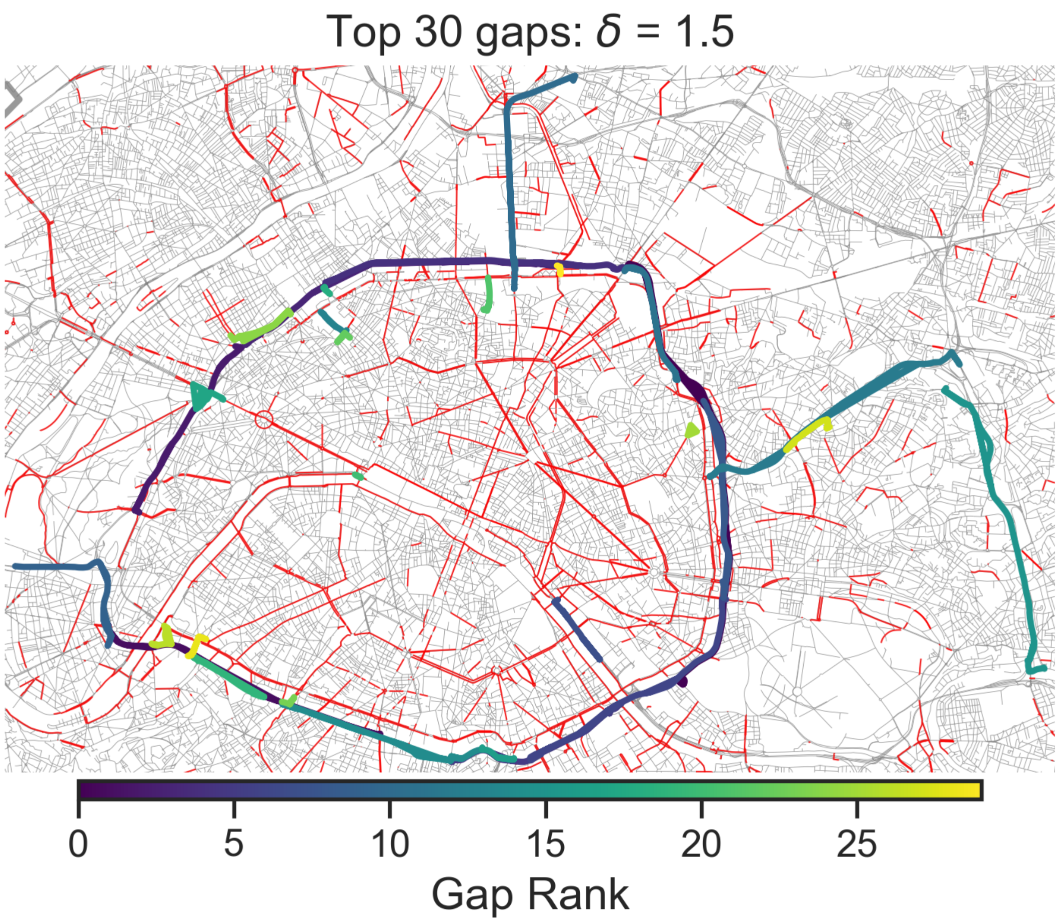

Figure 5.13.: Top 30 gaps for the baseline scenario of adults commuting to work. The road network is shown in grey and the bicycle infrastructure is in red.

Changes in the top 30 gaps through the introduction of equity

As mentioned above, the most important gaps are big stretches along the ring road. However, the smaller gaps on this road either disappear from the top 30 or lose ranks within it as equity is introduced. These small stretches of road thus likely linked areas of high population density with areas of high employment, without being relevant to vulnerable populations.

To illustrate the appearance of gaps as equity is introduced, Figure 5.14 shows the top 30 gaps for the scenario with $\delta = 1.5$ and the median income of each IRIS while indicating which gaps appeared in which equity-weighted scenario. Since the only change between the baseline and the equity scenarios is the introduction of the median income in the determination of the demand, the median income suffices to explain the results.

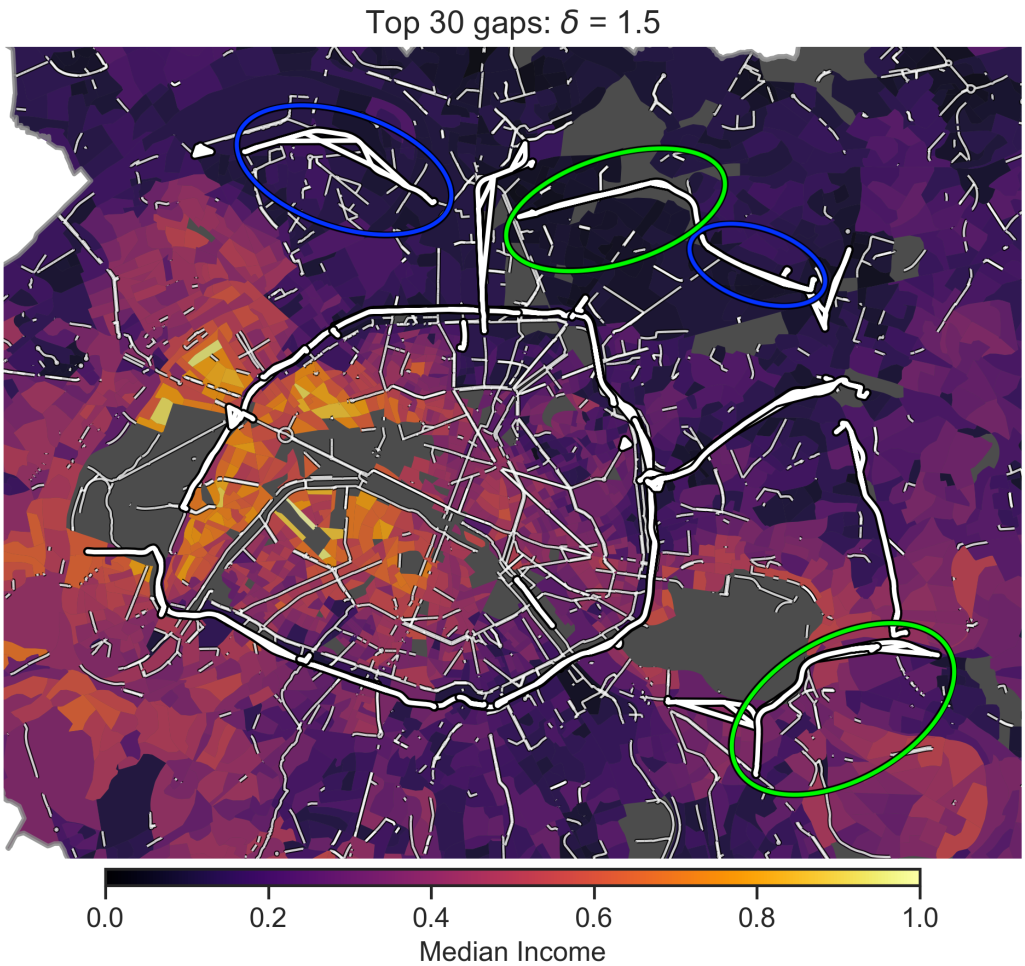

Figure 5.14.: Top 30 gaps for the maximum equity scenario of adults commuting to work (thick white), bicycle network (white), and median income (gradient) in the area. The gaps appearing in the scenario with $\delta = 0.5$ are circled in green and those that appeared in the scenario with $\delta = 1.5$. are circled in blue.

As soon as equity is introduced ($\delta = 0.5$), two big gaps appear in the top 30: one to the northeast of the city and one to the southeast. As illustrated in Figure 5.14 where they are circled in green, the gap to the North-East is in the lowest median-income area, and the gap to the South East helps link low median-income areas from the East to the high job density areas to the West. The gap to the southeast can be seen in Figure 5.12 to extend a bicycle lane that connects to the ring road. Once equity is introduced more heavily, another gap appears to the North East, extending the gap identified in the scenario with $\delta = 0.5$, and another one appears to the North-West, a low-income area close to high-income areas of the region.

Besides the changes explained in this and the previous experimental results, two types of changes are not analyzed in detail, namely the change of rank and slight changes in the exact itinerary of the gap. The first change is not considered here because, despite a change in rank, the gap remains in the top 30 of over 250 gaps, indicating that it is still of great importance. The second change is not analyzed in detail here as it could be due to the clustering algorithm being overly sensitive. The relevance of a gap for our analysis is not dependent on its exact itinerary: as long as it connects the same areas and roughly follows the same path with and without equity considerations, there is no need to analyze the minute changes. The clustering heuristic may not be adapted to such a fine-grained network due to the use of a simplistic shortest paths algorithm when routing between IRIS centroids. A dedicated transport assignment algorithm, which represents reality more accurately, may be more adapted.

5.3. Experiment 2: Children commuting to school

After declustering the top 10000 gaps for each scenario of children commuting to school, between 275 (baseline) and 305 (equity case with $\delta = 1.5$) remain to analyze.

Evolution of the Closing Benefit Metric over the identified gaps

The closing benefit value for the remaining gaps, shown in 5.15, falls to almost a third of its highest value between the top and the 10th gap, then stabilizes until the 30th before falling sharply again until the 50th. Although the top 50 gaps could be analyzed, the decrease of the closure benefit metric to a tenth of its value by gap 50 indicates that the analysis of the top 30 gaps suffices. Their closure benefit metric is shown in detail in Figure 5.16.

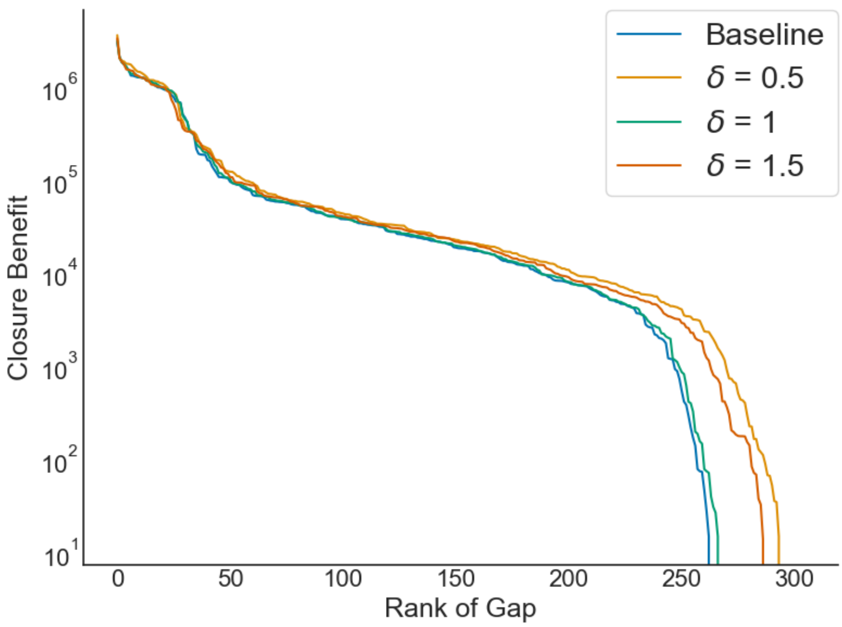

Figure 5.15.: Closure benefit of the remaining gaps after declustering for all scenarios of children commuting to school

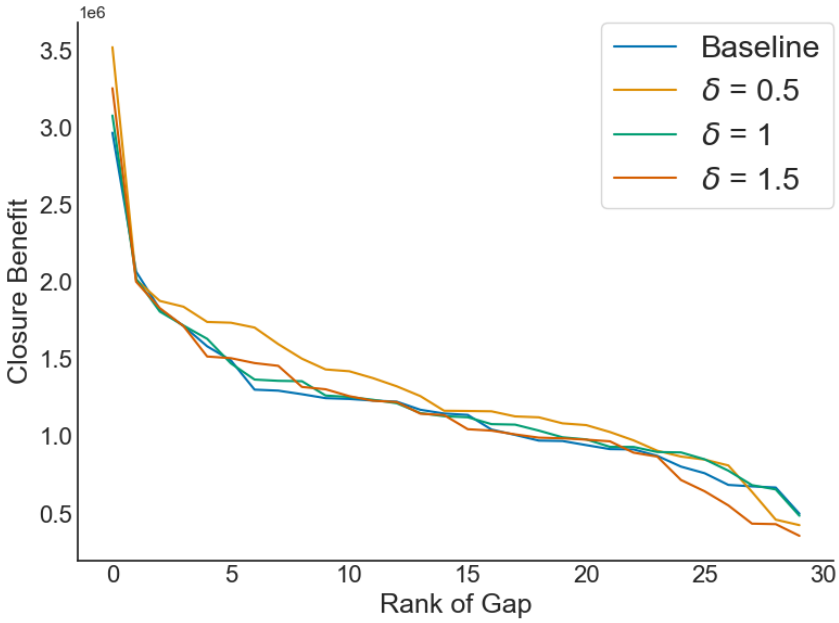

Figure 5.16.: Closure benefit of the top 30 remaining gaps after declustering for all scenarios of children commuting to school

Analyzing commonalities of all scenarios

The top 30 gaps of all scenarios for the experiment of children commuting to school are concentrated in the same area around the city of Paris as shown in Figure 5.17. All subsequent figures will focus on that area for clarity.

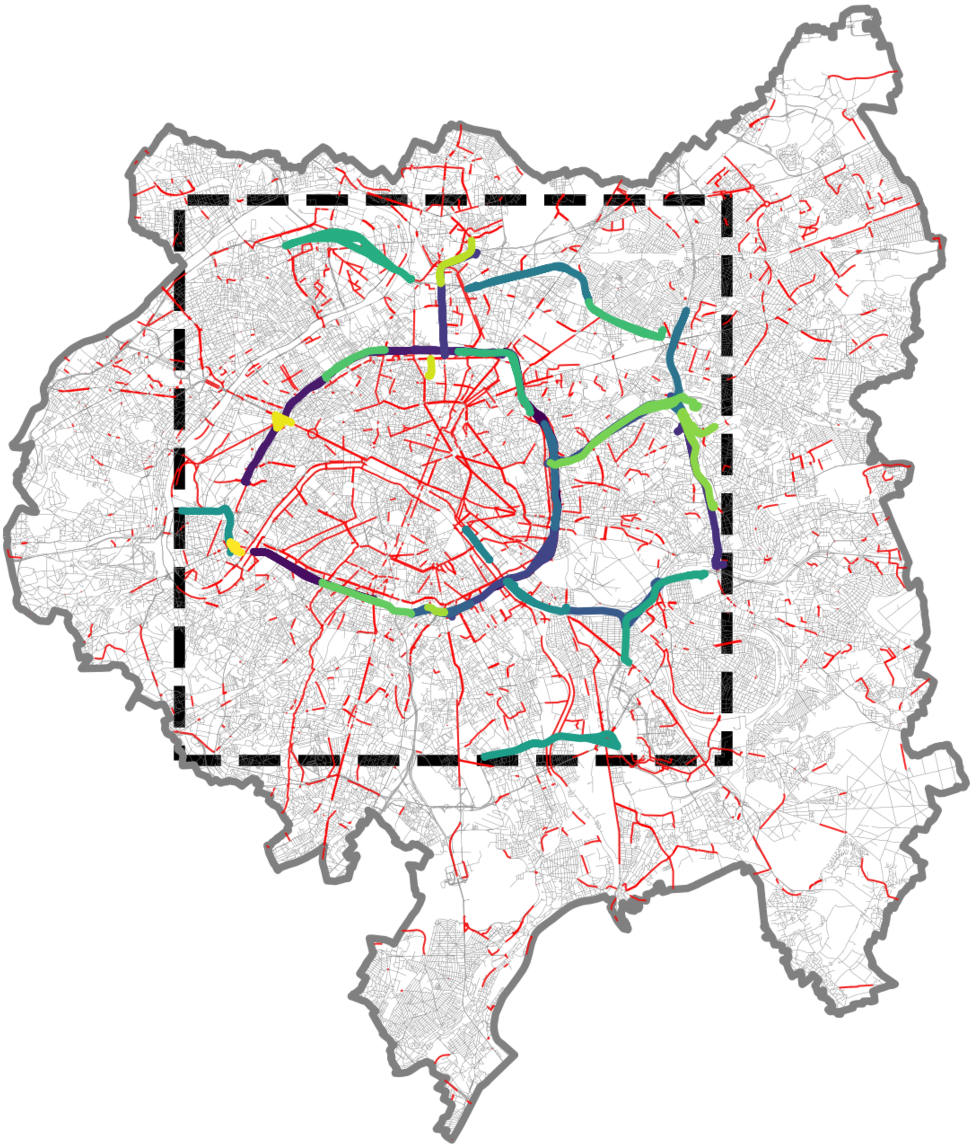

Figure 5.17.: The Grand Paris Metropolis with its road network (grey), its bicycle network (red), the top 30 gaps for the maximum equity scenario for reference (purple to yellow gradient), and the area that contains all top 30 gaps regardless of the scenario (dashed rectangle).

Similar patterns emerge for this experiment as for the previous one. The most important gaps follow the limit of inner Paris along the Boulevard Périphérique, the next gaps in terms of importance tend to be long stretches of road linking primarily northern and eastern suburbs to this ring road, and the least important ones in the 30 tend to be a piece of a bigger, more important gap on the Boulevard Périphérique. The same conclusions can be drawn and will not be repeated here.

The similarity between the patterns emerging in both experiments regardless of the equity scenario hints at the fact that the topology of the road network has a heavy influence on which gaps to prioritize. This is expected since the shortest path between origin and destination is calculated along the network. However, it also hints at the fact that certain road links have a disproportionate role to play in traffic between different areas of the Metropolis, which could lead to congestion and suggests that the development of new road segments could be beneficial for the overall flow of traffic in the Metropolis.

Analyzing the top 30 gaps

There is surprisingly little difference in which gaps need closing with and without introducing equity. This is shown in Figure 5.18, where the top 30 gaps are shown for the baseline scenario and the strongest equity scenario with $\delta = 1.5$. The other scenarios are shown in the appendix, as they are very similar to the ones in Figure 5.18. Only one gap is added to the top 30 when introducing equity, namely in the North East of the city. A small gap at the South West of the ring road disappears when introducing equity. Besides those minor changes, no further gaps enter or leave the top 30. Instead, the ranking of the top 30 gaps is changed. A higher value of δ or a different definition of the education level may be needed to induce stronger changes.

The gaps outside of the inner city all gain importance as equity is introduced. This indicates that they are more important to vulnerable populations than those on the ring road. Since children likely commute shorter distances than adults, it is understandable that the big ring road linking opposite sides of the city is of less importance in this experiment than in the previous one. To illustrate the relationship between the changing gap ranking and the education level, Figure 5.19 shows the top 30 gaps for the scenario with $\delta = 1.5$ and the education level of each IRIS.

As seen in the EDA and confirmed by Figure 5.19, the IRISs to the North and the South of the inner city have a lower education level than the area in between. This explains why the appearing gap is to the North East, why the disappearing gap is to the South West on the ring road, and why the gaps in the periphery of the inner city gain importance as equity is introduced.

Just as for the experiment of adults commuting to work, slight changes in the exact itinerary of gaps are not discussed.

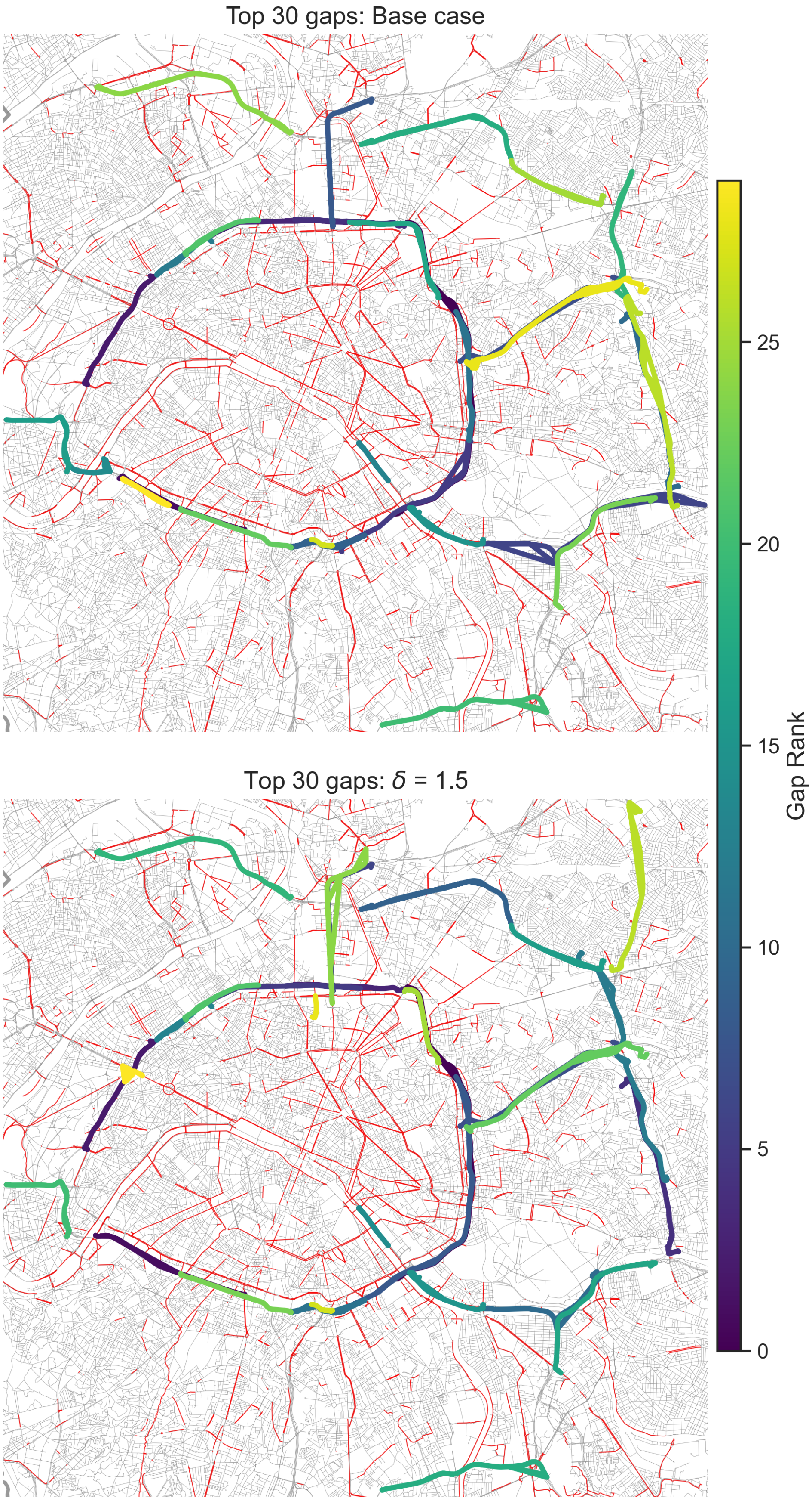

Figure 5.18.: Top 30 gaps for the baseline and the strongest equity scenario of children commuting to school. Only one gap appears (North East) and one disappears (yellow stretch of the ring road to the South West) when introducing equity, but most gaps outside of the inner city gain ranks.

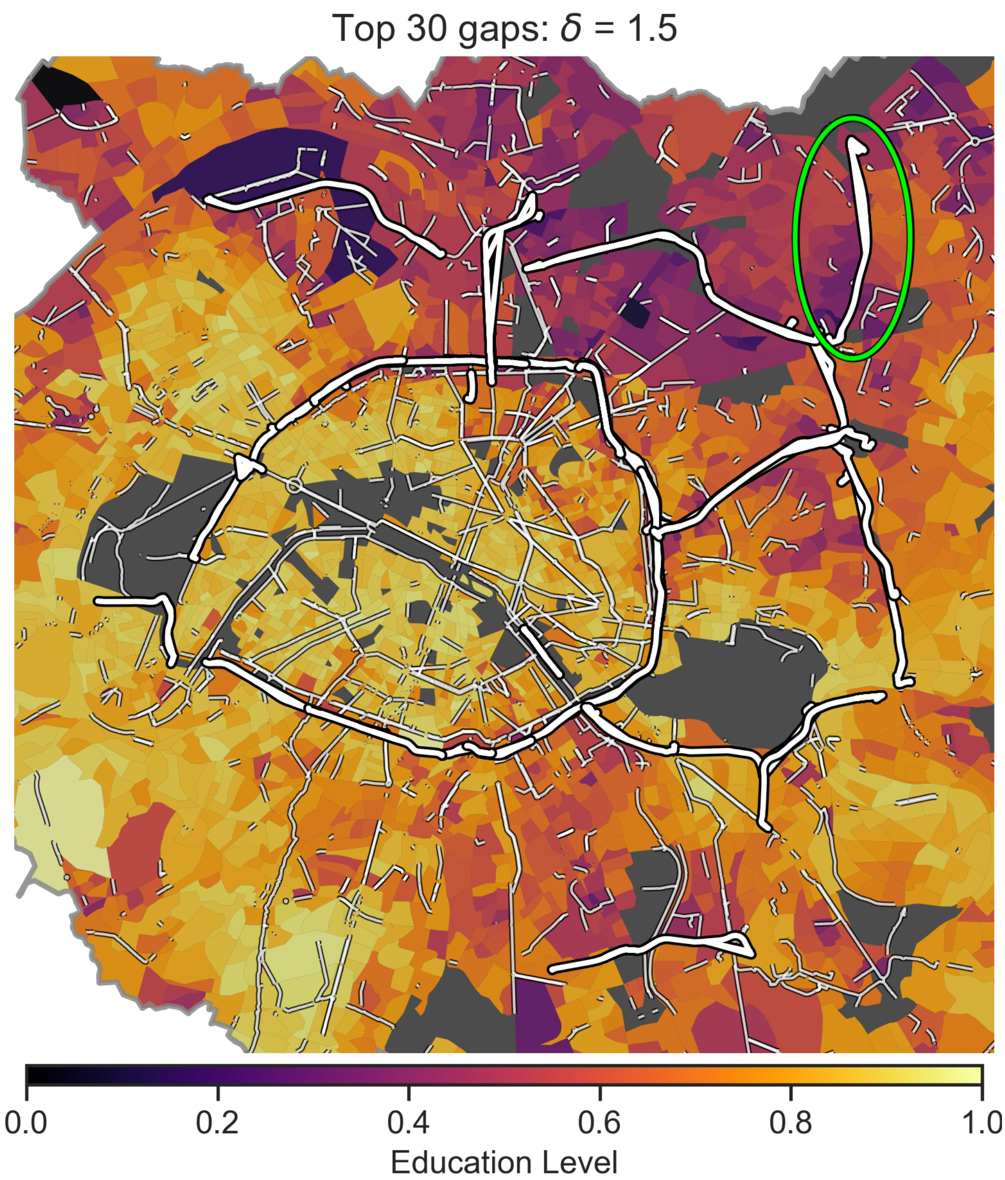

Figure 5.19.: Top 30 gaps for the maximum equity scenario of children commuting to school (thick white), bicycle network (white), and education level (gradient) in the area. The gaps in the periphery of the city gain importance in the ranking when equity is introduced, and the circled gap appears.

6. Discussion

6.1. Interpreting key findings

The Results described in the previous section provided a few insights into the role that equity may play when planning bicycle lanes usable by adults commuting to work or children commuting to school.

First, it was found that the benefit of closing gaps varies wildly, with certain gaps being orders of magnitude more beneficial to close than others according to the chosen closing benefit metric. Since resources are limited in government, the high variability in closing benefit hints at the existence of some (very) low-hanging fruit regarding the improvement of the bicycle network that should be tackled first. This is reflected in literature, as for example in Natera Orozco et al. [2020]'s work: starting with the current state of bicycle networks in multiple cities, they test multiple strategies to better these networks and found that *"small but focused investments allow to significantly increase the connectedness and directness of urban bicycle networks"*.

Second, it was found that the top 30 gaps in terms of their closing benefit are concentrated in specific areas of the Metropolis, regardless of scenario or equity. This too hints at the low-hanging fruit. The top gaps within the top 30 tend to follow two trends. On one hand, they may follow the Boulevard Périphérique, one of the most crucial roads in the area, circling Paris and significantly speeding up travel between areas on opposite sides of the city. On the other hand, they may connect areas outside of the inner city to this circular road. Gaps that do not follow these trends are usually farther down in the top 30 ranking, rarely far from the gaps that would connect outer areas to the ring highway. This means that the observed results mirror the topology of the road network in the Grand Paris Metropolis. This finding hints at the fact that the features of the existing road network largely determine the value of certain bicycle gaps and the decision of which gaps to place where must be carefully considered for each city. There will not be one-size-fits-all advice for every city. The Boulevard Périphérique is responsible for 7 of the top 10 bottlenecks in France [Pishue, 2022], hinting at its current importance for mobility in the Paris region and raising the concern that creating bicycle lanes on it would further worsen the issue. This calls for the creation of new road links and better transport alternatives (such as the bicycle!) to create redundancy and alleviate the pressure. Although the idea that the road network on which the bicycle network is mapped influences said bicycle network seems self-evident, it is also reflected in literature. Szell et al. [2022] developed a method to create coherent bicycle networks from scratch for any city, and they note that *"A transport network's geometry is its most fundamental limitation"*.

Third, gaps to the North West, North East, and South East of the city appeared in the top 30 gaps for adults commuting to work once equity was considered, but were already present in the top 30 gaps for the baseline of children's commutes, gaining in ranks as equity was introduced. This hints at the fact that different vulnerable populations can sometimes benefit from the same project, which could be a reflection of the compounded spatial concentration of vulnerabilities in the city. The EDA confirms this suspicion by showing overlaps between the areas with the lowest education levels and the areas with the lowest median income. However, the fact that different sub-populations can benefit from the same arrangements in the bicycle network even though said arrangements are not deemed useful to the general population can be described as the bicycle network equivalent of the curb cut effect. This effect describes how curb cuts, originally designed for wheelchair users, have become a staple in urban planning and are useful to many people other than the intended audience, such as elderly people or people with suitcases or strollers [Hesse, 1995]. Not only are more populations benefiting from these modifications than intended, but any population that is not actively helped by them is also not disadvantaged by them in any way. This is reflected in our results since usually the only gaps that drop from the top 30 when equity is introduced are subsets of bigger gaps that remain high in the ranking regardless of the scenario.

Fourth, it was found that the introduction of equity influences which gaps need to be prioritized. Certain gaps in top 30 before the introduction of equity were replaced by others once equity was introduced, hinting at their relevance being utilitarian (high population or school/job density areas) rather than egalitarian. The replacing gaps, which only reached the top 30 after the introduction of equity, show that certain gaps in infrastructure could be of major importance to vulnerable populations and play a key role in reducing urban inequalities. Although it may not be surprising that our findings overlap with those of the author whose methods we used, meaning Yap et al. [2021], it is still valuable to show that their findings on national level regarding road networks in 22 countries are also applicable to the bicycle network of one Metropolis. Certain segments are crucial for everyone's benefit, regardless of who they are, and some segments are of special importance to vulnerable populations without being of similar importance to the overall population. These findings also mirror those of Santos et al. [2008], who compared the development of new road segments on toy networks based on different equity measures and observed similar patterns to those we described.

Fifth and last, it was found that equity did not significantly change how gaps in the infrastructure should be prioritized. Although the introduction of equity does modify the top 30 gaps to close, it only does so to a limited extent. Less than 5 gaps, or under 20% of the top 30, were changed at most. This shows that the trade-off between utilitarianism and egalitarianism is not a difficult one to navigate, with minor changes in the original, utilitarian plan, already sufficing to satisfy a major part of the egalitarian considerations. This is also reflected in Yap et al. [2021]'s and in Santos et al. [2008]'s work.

6.2. Limitations of this study

Despite the great amount of care put into the conceptualization and implementation of this model, it has several limitations that must be addressed to nuance the key findings and recommendations. The model was also developed within the context of a broader approach that can also be criticized and improved in further work.

6.2.1. Limitations of the approach

The limitations of the approach can be broadly categorized in three directions and will be expanded upon below:

- The quantification of social concepts like inequality, vulnerability, poverty, and accessibility can always be criticized.
- Exclusively focusing on transport assumes that the city is static and won't be affected by transport measures (induced demand). It also fails to discuss the complexity of the solution needed to tackle the complex social issues at hand.
- The focus on cycling could turn into another greenwashing trend. Just like social issues, tackling climate change requires coordinated, radical, immediate and multi-faceted action.

Quantification methods will always over-emphasize or forget certain aspects of the term at hand, leading to model outcomes that do not fully align with the intentions set at the start. A good way to work through this limitation would be to involve the local population in the definition of the indicators. This would allow indicators to better reflect the reality of the people this study attempts to help and help avoid biases like those of CBA mentioned in chapter 2. Another improvement would be to involve more social scientists and more transport experts in the study to further ensure that the approach is fitting scientifically and aligned with the state-of-the-art in both fields of study.

The literature review presented in Chapter 2 defined the scope of this study. It should focus on bicycle lanes that can be used to commute in order to help reduce GHG emissions. Within that commuting scenario, it introduced the concept of vulnerability and specifically prioritized vulnerable populations in order to help reduce urban inequalities or at least not reinforce them. However, limiting the scope of this study does not mean that the solution to these issues mainly lies within said scope. Inequalities are complex, multi-faceted, and their specificities are dependent on the city of study. Truly tackling inequalities cannot simply happen through the smart placement of bicycle lanes or even through the smart development of an entire transport system. The solutions need to be as multi-faceted as the problem, involving more stakeholders, more fields of study, and more facets of urban life including governance structures.

GHG emissions come from a wide array of sources, and although personal transport plays a major role in Europe, it would be ludicrous to limit climate change action to the placement of bicycle lanes. Furthermore, tackling climate change requires quick and widespread action, the opposite of carefully planning bicycle lanes, waiting for a change in transport mode choice, and a cultural shift. Besides, these lanes could easily turn into the next greenwashing trend, making the city look a lot more eco-friendly than it is, and allowing policy-makers to point at the great efforts they are doing whenever their lack of climate action is criticized.

6.2.2. Limitations of the model

First, the defined indicators have a major impact on the outcomes of the model. For example, comparing the numerical distribution of the median income and the education level can partly explain why the changes in gaps resulting from the introduction of equity were so different for both experiments. A numerically evenly-distributed indicator seems to yield more changes than a heavy tailed one. As mentioned in the EDA, this could be due to the very high or very low average value, resulting from a heavy tail, which is used in the equity-weighted demand. It is dififcult to prioritize a group with a lower-than-average value for a certain indicator when almost the whole groups is below average. It is also worth wondering whether the distribution of the indicator simply shows that discrepancies in the relevant field are not the issue that should be prioritized the most. Maybe the children's scenario would yield more contrasted results in a different area using the same indicator. Further work could address this limitation by changing the chosen indicators in this area, applying this study to a different area, or a combination of these options.

Second, the choice of the model could be improved. The work of Vybornova et al. [2022] was specifically done with mature cycling networks in mind, and the Grand Paris Metropolis does not have a mature cycling network. It is very scarce and disconnected, yielding a much higher number of gaps than what Vybornova et al. [2022]'s method was planned for. The gaps themselves are also much longer than the ones from their work due to the change from a cut-off model (use of cut-off value λ) to a gravitational one as well as due to the immaturity of the cycling network leading to much longer distances being common between contact nodes. Applying a method on a network that does not fit its development context was a gamble, and future work could look into two improvements. On one hand, applying our methods to a more adapted network could help test whether the effects of the introduction of equity in this research were hampered by the incompatibility of the network and the method. On the other, a different method could be developed specifically for more scarce networks, as attempted by Vybornova's colleagues Szell et al. [2022] and Natera Orozco et al. [2020]. Their works were not adapted to this research due to either ignoring the current infrastructure [Szell et al., 2022] or being more difficult to expand with equity considerations [Natera Orozco et al., 2020].

Third, assuming the choice of model was justified despite the limitations just mentioned, the clustering heuristic was already a weak point in Vybornova et al. [2022] work, and no attempt was made in this study to improve it. It is unclear whether the gaps were declustered properly since many gaps overlap in the top 30, but it is also unclear how to better the situation. Further work could attempt to improve the declustering heuristic, though we suggest they do so on the Copenhagen case, not on the Grand Paris Metropolis. It is possible that the current method of applying a shortest-path algorithm to a network as fine-grained and as well-connected as the road network of a city is already problematic and the main reason why the declustering heuristic is not optimal.

Fourth and last, the quality of the data sources has a great influence on the quality of the results. For the sake of reproducibility and openness, only publicly available data was used. However, crowd-sourced data, like that of Open Street Maps, is not checked for quality and completeness, so it may contain flaws or inconsistencies that we are not aware of. In a study focusing on equity, it would seem logical to prioritize data that does not show more bias than is strictly necessary. The other datasets, taken from the INSEE, can be assumed to be correct, but it would always be an improvement to compare multiple datasets for quality or have an expert validate the data used.

The model itself has limitations that could be improved in future work, but it also draws from an approach that needs improving, which could exacerbate or nullify the need for certain limitations to be conquered.

6.3. Implications of this study

The results and limitations of this study can be used to improve multidisciplinary science and the policy-making process in sustainable development. Both types are presented in this section.

6.3.1. For science

This research attempted to combine two very different fields: on one hand, the mathematical field of network science, and on the other, the philosophical field of ethics. Although the work presented here is not the first to attempt this, as seen in the works of Yap et al. [2021] and Jafino [2021], it is a further test of the methods of this mixed field. Instead of assuming that the transport network is static and that all we can do is protect, expand, or reinforce certain links, we took their methods one step further and used them to plan the future modification of the network according to our goals.

A purely network-focused method, that of Vybornova et al. [2022], was adapted to include equity considerations, showing that models based on purely quantitative science can be expanded to include societal goals. The only obstacle to purposefully societally impactful models is the separation of sciences and scientists. The blind application of purely scientific models leads to unwanted societal impacts, and social sciences often lack the backing of quantitave methods to model the system at hand. With this research, we hope to encourage scientists and modelers from quantitative fields to expand their work, considering the wanted and unwanted societal impacts of their research and models. This may be the most impactful way to make science better serve society and help us achieve truly sustainable cities.

6.3.2. For society

This research has highlighted the role that specific policy decisions can play in the distribution of intervention benefits over different groups of society. It is crucial for policy-makers to truly understand which assumptions underlie their decision of going with one policy proposal over another. These assumptions include the definition of what is ”fair”, of which distributional outcomes they are aiming for, and of which goals are prioritized over others.

Focusing on utilitarianism, as is often privileged in policy-making and perpetuated by the standard methods of Cost-Benefit-Analysis, assumes that lifting vulnerable populations out of their situation is not nearly as important as achieving the greatest good, even if the corresponding utility only reaches populations that do not need help to achieve a better life. Although one can assume that no policy-makers purposefully decide to abandon vulnerable populations, a lack of understanding of the implications of assumptions leads to these unwanted, negative outcomes. The severity of the climate crisis, the real need for truly sustainable cities, and the growing inequalities in cities all call for more holistic approaches, better accountability for the consequences of policy-makers’ decisions, and overall a more thorough investigation of the effects of chosen policies.

6.4. Recommendations and future work

Now that we have discussed this research, its limitations, and implications at length, it is time to synthesize what was learned and look toward the future. What can be done with what was presented here?

We begin with what can be improved about our work in future endeavors. As was explained in the limitations of the model, the choice of indicators and their numerical distribution can play a huge role in the effectiveness of the method. Future work could test different indicators for the same experiment, maybe in different places as well, and shed light on which indicators yield the best results for which scenarios and in which areas. If that research delivers promising results, however, the next point of improvement would be the declustering heuristic of Vybornova et al. [2022]'s approach or the use of a shortest-paths algorithm on such a fine-grained network. As usual for data-driven models, much work could be done to further diversify the sources of data, increasing its quantity and quality, and ensuring that only the cleanest, least biased, and most appropriate data is used.

We continue with improvements that require fundamentally rethinking the methods used here. We decided to take two already-existing models and combine them, but maybe there are other models worth adapting, or maybe an entirely new model could be developed. If a new model is developed, it could be worth expanding the scope of this research to better encompass the lived experience of citizens of the Grand Paris Metropolis and elsewhere. The focus could be shifted from bicycle lanes only to a multi-modal system, allowing citizens to travel longer distances and make better use of the opportunities available everywhere in the city. The focus could also be shifted towards adapting these methods to different cities, shedding light on how differently justice can look based on the pre-existing conditions of the city.

For the sake of improving policy-making, it could be of great value to consider including relevant stakeholders in this research. They could help conceptualize the model in a way that is more conducive to policy-making, as well as validate the assumptions made through the literature review about how policy-making currently works. Another advantage of including policy-makers in this process would be what they learn through their participation. Their exposure to the different scenarios and their implications for justice could encourage them to better rethink their assumptions in their choice of method and goals, possibly improving their future endeavors.

7. Conclusion

In this chapter, the research questions set out in Chapter 2 are answered individually with the help of all insights gathered in the Chapters since then.

7.1. Sub-question 1

How can bicycle lanes that serve both for the reduction of GHG emissions and for the reduction of inequalities be conceptualized?

The goal of this question was to understand which characteristics were necessary for a bicycle lane to serve both goals. The answer to this question was already given in Chapter 4 and used to develop the model used in this research.

In order to combat GHG emissions due to transport, bicycle lanes have to be placed in such a way that they incentivize citizens to *replace* their car trips with bicycle trips. Given that the commute is the most common trip taken by citizens, connecting people to their place of work with proper bicycle infrastructure is likely the most impactful way of stimulating cycling to reduce GHG emissions from transport. Defining what is ”proper” bicycle infrastructure comes as a natural next step. In order to make cycling more attractive to women, who represent up to half of the working population and are thus a demographic well worth including, bicycle infrastructure must emphasize safety. This means that dedicated bicycle lanes segregated from traffic are the most likely to attract women cyclists. The completeness and homogeneity of the infrastructure play a huge role in cycling uptake.

Looking at urban inequalities, the main takeaway is that any intervention must be done with specific populations in mind, deciding exactly who to prioritize and which of their trips to prioritize. Shifting the focus from utilitarian methods like CBA to more egalitarian methods is fundamental.

In conclusion, the ”perfect” bicycle lane that combats both GHG emissions and urban inequalities has the following qualities:

- It is safe: segregated from traffic, dedicated to bicycles only, easy to understand, and clearly demarcated
- It is part of a well-connected network of bicycle lanes, allowing citizens to ride most if not all of their trip without needing to mix with car traffic or take major detours
- It is planned with vulnerable populations in mind and ensuring that those who need the infrastructure the most are served by it.

7.2. Sub-question 2

How would the bicycle infrastructure of a city develop without equity considerations?

When placing bicycle lanes to facilitate children's commute to school or adults' commute to work regardless of their socio-economic profile, two patterns emerge.

First, and likely due to the historical development of the road network in Paris, the most important gaps in the cycling network are those around the perimeter of the city. They roughly follow the Boulevard Périphérique, a major ring road heavily used by locals of the area to quickly travel between the inner city and its suburbs or between suburbs on opposite sides of the inner city. Bigger gaps along this path are of greater importance, but specific chunks of these long gaps could be closed first in order to already improve the quality of the cycling network tremendously. The disproportionate importance of certain links could also hint at some inefficiencies in the road network that could be solved by adding redundant links or modifying the land use (decentralisation) to limit the need for these links.

Second, the most important gaps for the city after those mentioned previously are those that connect close Northern and Eastern suburbs to the ring road, followed by gaps linking the extremities of Northern and Eastern suburbs to these linking roads.

Third, the simple separation of children's and adults' commutes is already enough to showcase differences in the planning of the bicycle infrastructure, even without introducing equity. Children are more prone to needing bicycle lanes in the suburbs than adults, likely due to their shorter commute and lesser need for the ring road.

These findings mirror the very centralized nature of the area as well as the disproportionate importance of certain road links for mobility towards and around the inner city. They also showcase how considering different populations regardless of equity already changes how the city is planned.

In short, the bicycle infrastructure of the city would develop according to characeteristics of the current road network, namely which links are the most used and should be turned into bicycle infrastructure to stimulate bicycle uptake.

7.3. Sub-question 3

How would the bicycle infrastructure of a city develop under different scenarios where equity is explicitly added to the current considerations?

The important segments of larger paths in the scenarios without equity lose their importance, but the underlying very important gaps remain the same. This is valid for both experiments.

In the children's experiment, only one gap that was previously considered unimportant becomes relevant when equity is introduced. This gap is not relevant for adults commuting to work regardless of the scenario. In the adults' experiment, four gaps appear in the top 30 when equity is introduced, namely in areas with low median income and usually linking these areas to roads that lead to the ring road. These gaps were already important in the baseline scenario of children commuting to school, hinting at the fact that helping vulnerable children commute to school also helps vulnerable adults go to work and reducing the amount of work needed to include these vulnerable populations into the considerations.

The introduction of equity does not lead to major changes in the planning of the bicycle network, showing that slight changes can positively impact the most vulnerable, and that those changes help multiple vulnerable populations at once. The most visible changes are the addition of some projects in the outskirts of the city.

7.4. Main Research Question

"How does including equity in transport planning change the development of the bicycle infrastructure?"

First, the development of the bicycle infrastructure will remain tied to the specific characteristics of the available network, even after equity is introduced and heavily prioritized. This means that if the road network is built in such a way that certain links are extremely important compared to others, introducing equity is unlikely to trump that importance enough to make a significant change in how the infrastructure should be planned. Whether this means that major roads should be turned into bicycle roads, that the city should decentralize, or that redundant roads should be built, depends on the specific city of study.

Second, the introduction of equity changes the prioritization of certain aspects of the bicycle infrastructure, but not to much effect. Small pieces of infrastructure close to the city center that were expected to be very important before the introduction of equity lost their importance once equity was introduced. These small pieces of infrastructure were then deemed less important than bigger projects outside of the city center. This means that the introduction of equity leads to a few projects being moved outside of the inner city. However, as mentioned in the paragraph above, the most important projects remained the same, meaning that introducing equity does not require major changes in the infrastructure. These are good news for policy-makers as it means that the achievements needed for environmental and social sustainability are not strongly conflicting and easily reconcilable. At the same time, it means that there is no excuse not to do so.

A. Data Sources and Cleaning

This Appendix describes the data used to create the model detailed in Section 4.

A.1. Open Street Maps

This section describes the procedure from the Jupyter Notebook named "1_Create_car_bike_networks.ipynb" in the GitHub repository of this project. Open Street Maps (OSM) was used to create the street network of the Grand Paris Metropolis (GPM) as well as to classify which street segments were bike-friendly or car-friendly as described in 4 Open Street Maps [2022]. This section was mostly achieved by adapting the publicly available code from the authors of Vybornova et al. [2022]. The library OSMnx was used to retrieve the latest available data on GPM and a small buffer around the city limits from OSM using the following tags:

1. barrier
2. bicycle
3. bicycle_road
4. crossing
5. cycleway, cycleway:left, cycleway:right, cycleway:both, cycleway:buffer, cycleway:left:buffer, cycleway:right:buffer, cycleway:both:buffer
6. foot, footway,
7. highway
8. name
9. osm_id
10. segregated
11. tracktype

Once retrieved, the network was reduced by removing some sub-categories of links tagged under "highway" that were not necessary to this analysis, such as private lanes or service roads. The sub-tags used to filter out unnecessary links and nodes under the "highway" category are:

1. highway == service
2. highway == path
3. highway == pedestrian
4. highway == footway

5. highway == elevator
6. highway == steps

Once the network was created, the tags were used to categorize all street links as either ”bike” or ”car” links. The following tags represent a bicycle-friendly link:

1. cycleway
2. segregated
3. cycleway in [’track’, ’separated’, ’segregated’, ’designated’, ’opposite_track’]
4. cycleway_left in [’track’, ’separated’, ’segregated’, ’designated’, ’opposite_track’]
5. cycleway_right in [’track’, ’separated’, ’segregated’, ’designated’, ’opposite_track’]
6. cycleway_both in [’track’, ’separated’, ’segregated’, ’designated’, ’opposite_track’]

A lack of bicycle-friendly tags or the presence of the ”dismount” tag indicates that the link is car-friendly. Next, the network is modified without loss of information to conform to the conceptualization from Vybornova et al. [2022]: all nodes are street intersections and all links are street segments between intersections. In order to achieve this, all nodes that are not intersections or dead-ends are removed. Then, any consecutive edges that are already between any pair of these nodes are used to create one edge between each of the relevant node pairs, conserving the geometry and type of the edges. This process is illustrated in Figure 4.1.

The last step in this process is to attribute a node type attribute to each node of the network, namely ”bike”, ”car” or ”both”, depending on which types of edges meet at each node. Figure 4.2 from the main text illustrates these definitions.

A.2. Administrative Output Areas

This section describes the procedure followed to create the administrative output area layer of the model. The corresponding Jupyter Notebook ”3_Add_socioeconomic_data.ipynb” is in the Github repository of this project. Open Street Maps was also used to retrieve the geometry of the Grand Paris Metropolis as well as the location of schools, but the rest of this model layer was created with data from the French National Institute of Statistics and Economic Studies (INSEE) or the French Organizations for the Collection of Social Security and Family Benefit Contributions (URSAFF). All datasets used and their sources are summarized in Table A.1.

The geometry and codes of the smallest possible administrative output areas of France (IRIS) were retrieved from the INSEE website (see Table A.1), then subsetted for those falling within the GPM borders retrieved from OSM. The centroids were added using the GeoPandas library, and these centroids are used in the model as the start and end of all trips.

Table A.1.: Data sources used for this research

Data Type	Data Source
Grand Paris Metropolis shape	OSM and OSMnx
IRIS shapes	French Geoservices
Road and Bicycle networks	OSM and OSMnx, tags in text
Number of schools per IRIS	OSM and OSMnx, tags in text
Median income per IRIS	INSEE dataset "Income, poverty and cost of living, 2019"
Education level per IRIS	INSEE dataset "Diplomas and education, 2019"
Population per age range	INSEE dataset "Population in 2019"
Number of people employed in each commune (divided per IRIS later)	URSAFF dataset "number of employing establishments and salaried employees of the private sector per commune 2006-2021

Once the centroids are created, socio-economic information and POI numbers of each IRIS are retrieved:

1. The location of 4245 schools was given by OSM using the tag "'amenity': 'school'", which were then grouped by IRIS
2. URSAFF data delivered the number of jobs per commune (one level higher than IRIS). The number of jobs per commune was evenly distributed over the IRISs within each commune
3. The median income in 2019 was retrieved on an IRIS level from INSEE data, missing values were completed with commune-level data from the same source.
4. The education level was defined as the inverse of the proportion of people out of school and above 15 years of age without any diplomas. This was calculated based on INSEE data. The missing values were filled in with values from the neighboring IRISs since they all belonged to the same commune.
5. The active and school population densities were calculated using data on the structure of the population in 2019 from INSEE.

A.3. Bringing the layers together

The final model was created by putting all nodes and edges from both layers into one network using the NetworkX library and linking both layers together using SnKit. The procedure is shown in the Jupyer Notebook named "2_Combine_into_final_network_and_IP.ipynb" in the Github repository of this project. For practical reasons, the identification of gaps also takes place in that notebook.

B. Figures from the Results Chapter

B.1. EDA

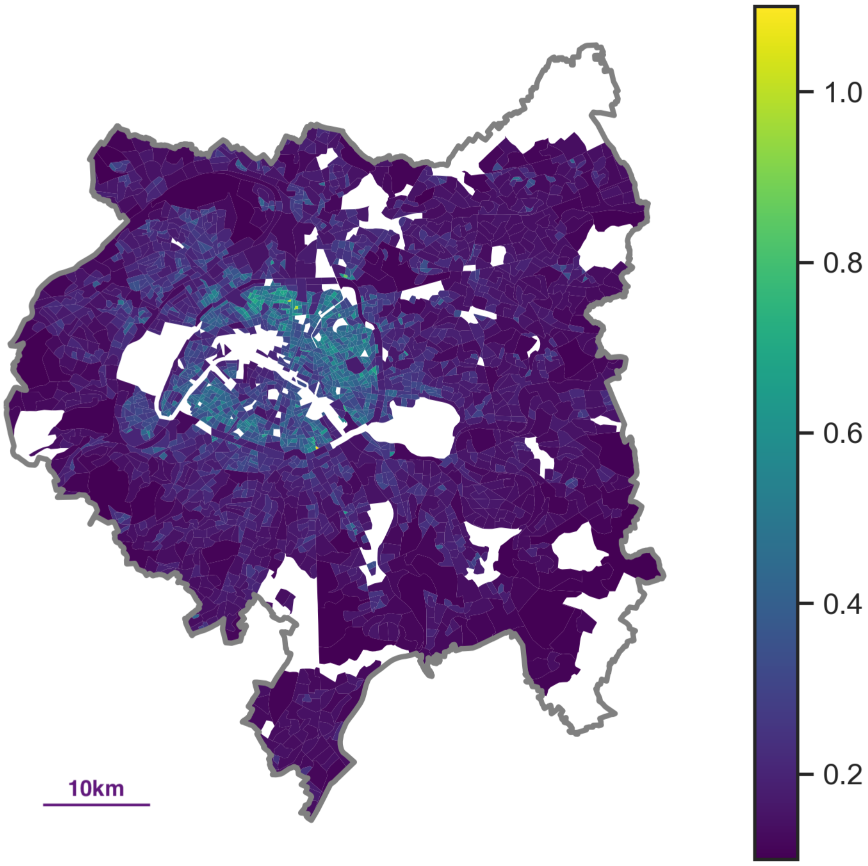

Figure B.1.: Active population density of the Grand Paris Metropolis

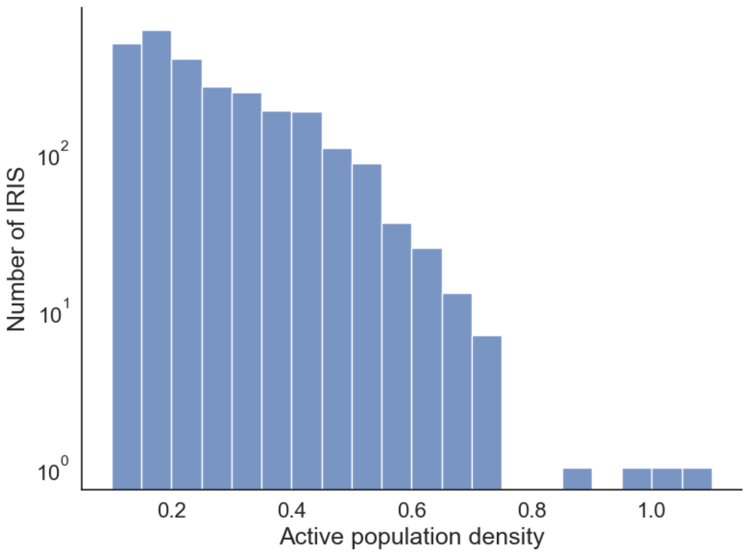

Figure B.2.: Numerical distribution of the active population density in the Grand Paris Metropolis

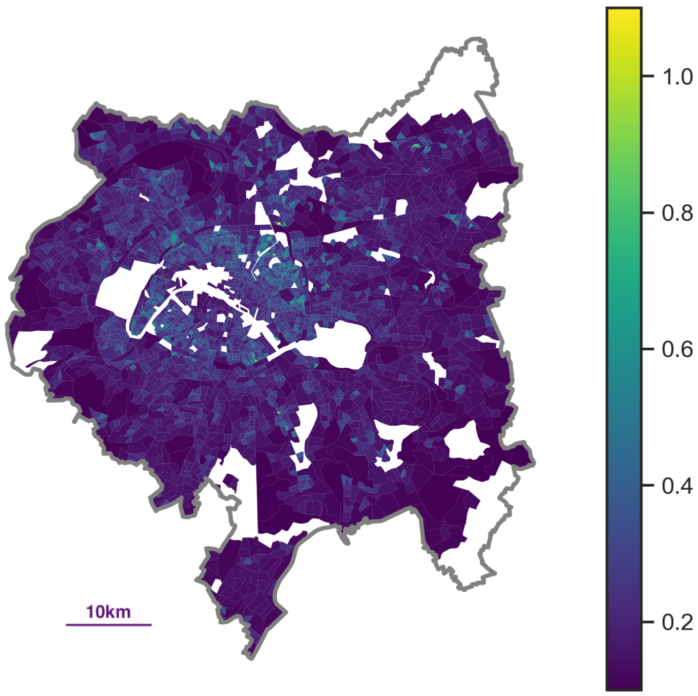

Figure B.3.: Geographical distribution of the school population density in the Grand Paris Metropolis

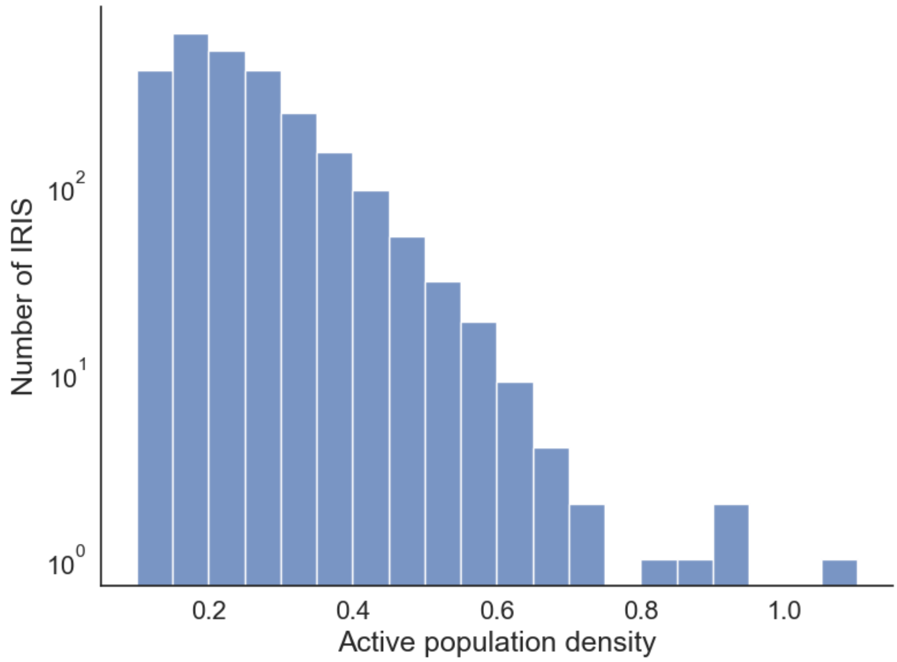

Figure B.4.: Numerical distribution of the school population density in the Grand Paris Metropolis

B.2. Experiment 1: Adults commuting to work

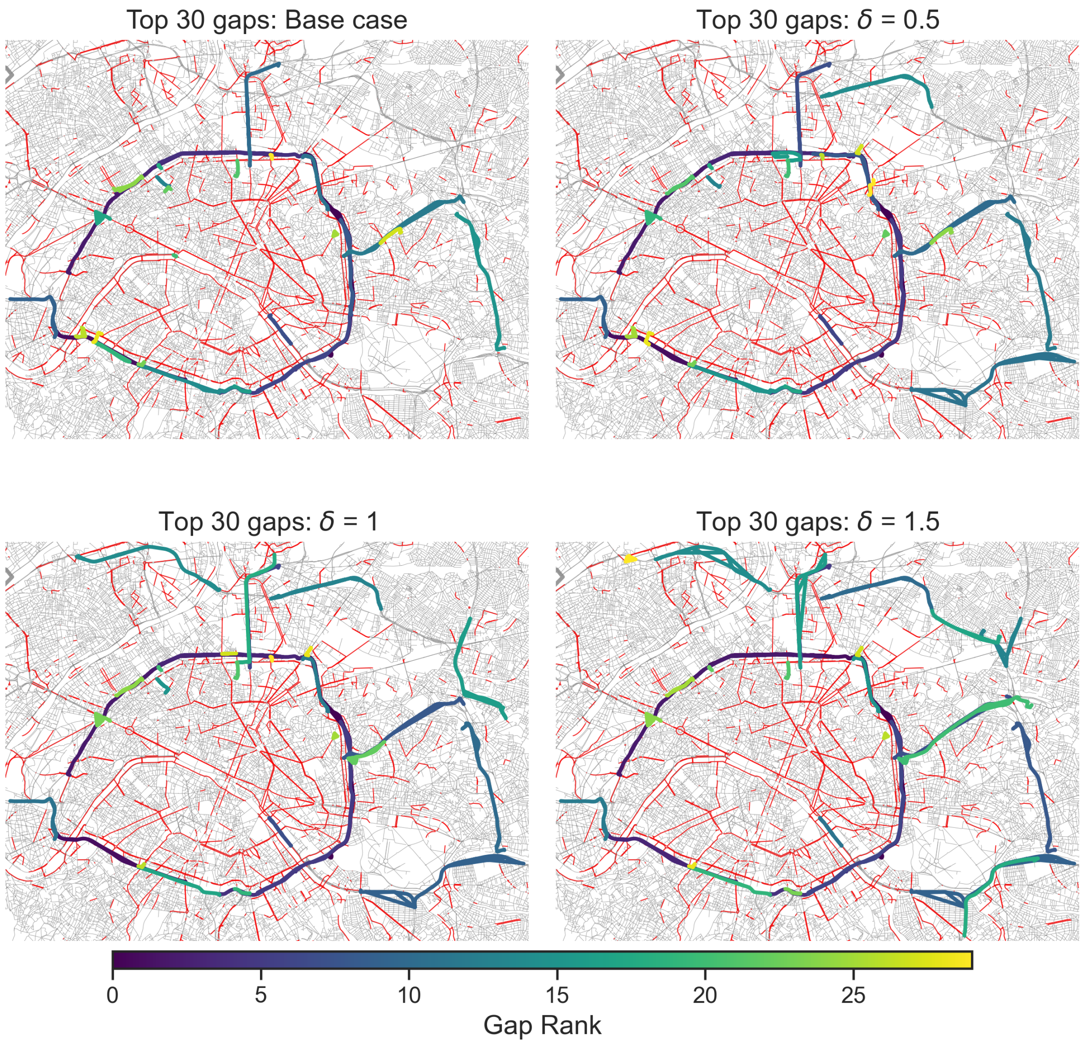

Figure B.5.: Top 30 gaps for all scenarios with and without equity focusing on adults commuting to work

B.3. Experiment 2: Children commuting to school

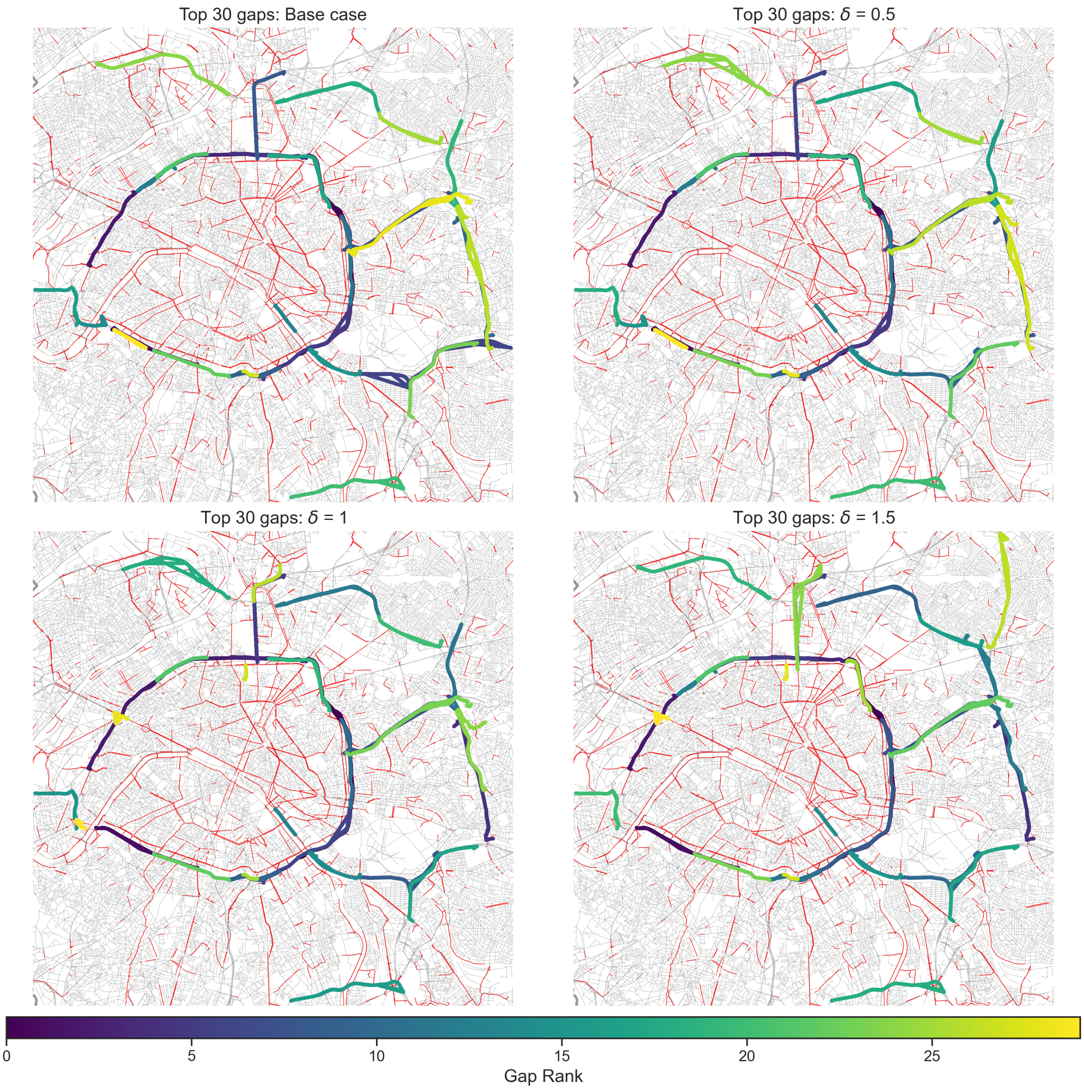

Figure B.6.: Top 30 gaps for all scenarios with and without equity focusing on children commuting to school

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