Exploring the geographical equity-efficiency tradeoff in cycling infrastructure planning

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Abstract

Cycling is affordable, healthy, and sustainable, but access to destinations on low-stress safe cycling routes in most cities is both limited and unevenly distributed. Many cities are expanding cycling networks to improve safety, increase cycling mode share, and increase diversity in access to cycling, however resources remain limited which requires prioritization of infrastructure. When proposed infrastructure locations are optimized to provide the highest average access to opportunities using a utilitarian definition of accessibility, marginalized groups and locations may be further left behind. This occurs since the greatest gains to network connectivity, using a utility definition, come from expansions inside or directly adjacent to the densest network areas. We compare utilitarian and equity-driven planning strategies for cycling network expansion and explore tradeoffs in spatial coverage, equity, and efficiency, using Toronto, Canada as a case study. We find that optimizing accessibility in several small regions instead of city-wide leads to an infrastructure plan that is more spatially distributed.

Further, we show that a model targeting low-access areas produces an infrastructure plan with more regions meeting a minimum threshold of accessibility but with lower average accessibility gains, indicating the presence of an equity-efficiency tradeoff. We also find that infrastructure projects that maximize a region's accessibility to destinations are often located outside that region, challenging political perceptions of 'local' infrastructure and benefits. These results inform planning, advocacy, design, and policy, and shed light on spatial and socio-demographic equity tradeoffs in deciding where to add cycling infrastructure.

Keywords: Cycling, Infrastructure, Equity

1 Introduction

Cycling is an affordable and sustainable mode of transportation which benefits health [1], alleviates congestion and pollution [2, 3], and provides affordable access to transportation systems [4]. The presence of safe and comfortable cycling infrastructure in cities is a strong determinant of ridership [5, 6, 7], but many jurisdictions lack a comprehensive and connected safe cycling network [8]. Many regions around the world including Paris [9], the UK [10], Bogota [11], Toronto [12, 13], Ottawa, Vancouver [14], and Montreal [15] are expanding cycling networks with the goal of encouraging people to cycle.

Cycling infrastructure planning has traditionally been qualitative, relying on criteria based on local knowledge to score a shortlist of candidate projects [16, 17]. Even small increases to cycling infrastructure tend to be hard-fought and can be politically contentious [18, 19]. To make a strong case for new infrastructure and effectively evaluate its impact, there is increasing interest in developing quantitative approaches to better prioritize infrastructure with limited budgets. Emerging quantitative techniques include Level of Traffic Stress to identify parts of the network that are particularly ill-suited for biking [20] and optimization techniques that promise efficient solutions for a given goal [21]. However, these techniques may produce efficient solutions by their chosen metric at the cost of solutions that improve equity or other goals. Not explicitly including an equity focus when optimizing transportation networks may even reinforce and deepen existing inequities [22, 23].

This paper contributes to the gap in current quantitative cycling infrastructure planning techniques by incorporating equity into a previously-developed data-driven optimization model [21]. We show that utilitarian vs. equity-driven optimization goals produce spatially distinct infrastructure plans and that marginalized and privileged groups benefit differently from different optimization goals. Recent work has highlighted that several commonly-used equity metrics can lead to contradictory interpretations of an infrastructure or service change [24]. In light of this, we measure and report multiple equity metrics for distinct sub-groups to give a more complete picture of the impact of network design decisions. We derive policy insights from our methods that highlight the impacts of the spatial scale of planning and challenge the political perception that people can only benefit from infrastructure close to them.

1.1 Contributions

- We contribute quantitative data-driven methods for cycling infrastructure planning that 1) use Level of Traffic Stress to capture a holistic view of the cycling network and 2) use accessibility to destinations to measure the functional impact of infrastructure.
- We introduce approaches to overcome biases in traditional optimization that disregard equity in favour of maximum utility. We illustrate this approach using Toronto, Canada as a case study, but these methods are general and applicable to any region for which a Level of Traffic Stress map can be constructed.
- We derive policy insights from the various optimization methods introduced in this work: 1) we show that infrastructure projects that benefit a region aren't necessarily located within that region, challenging commonly-used metrics of infrastructure impact and political conversations around infrastructure; 2) we contribute quantitative methods to measure the impact of infrastructure; 3) we illustrate potential benefits and tradeoffs of different optimization criteria.

1.2 Approaches to transportation network expansion

How do cities decide where to invest in transportation infrastructure? Traditional car-based transportation planning uses models of travel demand to predict which areas of the network will experience a lack of capacity [25], but many of the approaches that have been used for car-based network planning are not appropriate for cycling. There is a wide variety of abilities, comfort levels, bicycle designs, and travel speeds among people who bike, from toddlers on balance bikes to people with clip-in pedals and road bikes to people using cargo or electric bikes and beyond [26]. Almost all built car infrastructure is suitable for driving, but cycling is much more sensitive to environmental conditions — just because cycling is legally permitted on a piece of infrastructure doesn't mean people will cycle there [6]. There is also variety in what is considered adequate cycling infrastructure, from designated "slow streets" to off-road paths (that might be shared with other modes) to painted on-street bike lanes to barrier-protected cycle tracks. Predictions of induced cycling demand have remained rare in research and practice. In addition, car infrastructure planning typically groups origins and destinations at the level of Traffic Analysis Zones, which tend to be larger than the smallest census unit and can represent cycling travel times that are too long for meaningful analysis [27, 28].

Cities typically use a series of hand-picked criteria to score a shortlist of candidate projects chosen based on local knowledge, domain expertise [16, 17], and real-world factors such as political and community consultation and coordination with other road projects [29]. Over the last decade, and particularly the last few years, there has been effort to mature the quantitative planning and analysis tools for cycling infrastructure and cycling mode choice [30]. Some have used approaches inspired by traditional car-based planning to estimate cycling demand on particular road segments based on current cycling usage [31, 32, 33], though using current demand to forecast future demand does not capture induced cycling due to infrastructure improvements [34]. Several studies have identified and quantified "gaps" in cycling networks using various methods such as measuring the length of travel distance possible in connected sub-networks [35] or quantifying discontinuities due to infrastructure or environment changes [36]. The possibility of prioritization following these analyses was implied, but an actual ranking of proposed infrastructure was not performed. Work that explicitly proposed specific infrastructure investments [37, 8, 33, 38, 39] has not included measures of destination desirability: the focus has been on achieving spatial properties (such as improved safety or network completeness) independent of land use. In contrast, we use accessibility to destinations on a low-stress network which captures both potential demand for destinations and the features of the network that make cycling comfortable and safe.

1.3 Accessibility to destinations and Level of Traffic Stress

In this work, we focus on the distributional spatial and demographic equity of a cycling network by measuring accessibility to destinations. Accessibility to destinations [40, 41] is a method of measuring the benefits of transportation systems that is increasingly popular for understanding the functional impact of cycling infrastructure [7, 42, 43]. Accessibility to destinations captures the range of available opportunities in a network rather than relying on observed or predicted behaviour [40, 25, 44, 45, 46, 47, 48]. A reliance on behaviour and travel demand may be misleading; for instance, using car ownership as a measure of ability to travel by car may mask the presence of forced car dependence where people lack viable alternatives but are trapped in poverty by the costs of car ownership [49, 50]. In the case of cycling, predicting demand often relies on either existing cycling trips or existing short car trips [30, 51, 52, 31, 32, 33], but cycling is extremely elastic to changes in infrastructure [34] and depends on other social factors such as rider gender [53, 54], age, and ethnicity [54], making such predictions difficult. In contrast, accessibility to jobs on a low-stress cycling network captures real opportunities regardless of existing travel patterns, is correlated with cycling mode choice [7], and is predictive of employment [55] and activity participation overall [56].

Decision-makers and researchers widely use distance to cycling infrastructure and the overall amount of cycling infrastructure in a region as a measure of access to cycling [35, 57]. However, these measures do not capture the actual usefulness of infrastructure (where it goes and what it connects to) and conversely do not consider the functional value of safe low-stress streets *without* infrastructure. In this work we use Level of Traffic Stress (LTS), a rating system for the cycling experience on roads and paths, to overcome these gaps and more accurately evaluate the functional attractiveness of the road network for cycling. LTS categorizes all streets on a scale of 1 (comfortable for a broad range of cyclists including children) to 4 (uncomfortable for most cyclists) based on physical characteristics such as the number of car lanes, vehicle speed and volume, and presence and type of cycling infrastructure [20]. Importantly, some low-traffic and low-speed streets without any dedicated cycling infrastructure may be considered low-stress and form important cycling links [58]. In line with previous work using LTS, we consider LTS 1 and LTS 2 "low-stress" and suitable for most adult cyclists [7, 43].

1.4 Incorporating equity in transportation network design

Equity ought to be considered at multiple stages of the transportation design and planning process. This includes procedural or representational equity – who is involved in or missing from decision-making and whether equity-seeking groups perceive benefits from projects, and distributional equity – which people and groups receive either the harms or benefits of the transportation system [59]. Within the framework of distributional equity, much research has focused on the disproportionate negative externalities of transportation infrastructure such as pollution, noise, or safety risks [60, 61]. Recently, there has also been focus on ensuring that the *benefits* of transportation improvements are delivered equitably. Travel capabilities differ based on many social factors such as income, abilities, and access to certain types of vehicles, and new work is taking an equity focus by considering the real benefits that a transportation system provides and who does and does not have access to them [62, 46]. Inequitable access to transportation and infrastructure can lead to suppressed travel and social exclusion when people are not able to fulfill their travel needs [46].

Existing patterns of cycling infrastructure in many cities reflect historical patterns of investment and land use [63, 64, 65]. For instance, many bike sharing systems have been rolled out in downtown areas first and only later expanded to outer areas and more marginalized areas [66]. In combination with inequitable land use patterns that in recent decades have led to wealth concentration in downtown areas for many cities [67], this has led to inequities in who has access to infrastructure and destinations, both spatially and socio-demographically

[4, 68]. Additionally, not explicitly including an equity focus when interpreting data or implementing algorithms can give misleading or even harmful results by reproducing or reinforcing existing inequalities [22, 23, 69].

There may also be a trade-off between equity and efficiency, a phenomenon that appears in many domains when choices are made about how to spatially distribute limited resources [70, 71, 72, 73]. Equity-efficiency tradeoffs are notably absent in some cases, for example housing allocation [74] and AED placement [75], where it is often possible to improve the situation of the most marginalized individuals without any loss of possible benefit to the most well-off. This is thought to happen because there are many functionally equivalent improvements that could be made, and choosing the one that best improves equity does not introduce a tradeoff in the overall impact [74]. We investigate both the overall efficiency of our models and their impacts on equity metrics to identify whether such a tradeoff exists in cycling infrastructure allocation.

In practice, cycling network plans only sometimes incorporate an equity lens [76, 77], though equity in access to cycling infrastructure has been considered in previous research, most commonly in work that explores group differences in costs, benefits, and access to cycling infrastructure [4, 60, 78, 79]. In line with measuring equitable access to existing infrastructure, works that have incorporated equity specifically in network design have primarily evaluated the proximity of equity-deserving groups to infrastructure without measuring the functional improvement provided by network changes [80, 69, 51, 81, 82]. Optimizing for a functional metric such as connectivity [52, 83] or accessibility [71] while also considering equity remains rare. Proximity-based measures have two flaws in the context of infrastructure planning. First, they do not capture the impact of spatially distant infrastructure that people may use while travelling between two places, and this becomes more significant for modes with higher travel speeds (such as biking compared to walking). Second, proximity-based measures do not capture the function of a network; a region could receive a high proximity score from being next to a disconnected stump of cycle track. Our paper overcomes these limitations by directly optimizing for and measuring accessibility to destinations to generate a meaningful understanding of the network-level impact of infrastructure.

Though reaching community consensus on standard metrics of equity is neither possible nor desirable, recent work has highlighted that several commonly-used equity metrics such as the Gini coefficient and needs-gap analysis can lead to contradictory interpretations of an infrastructure or service change [24]. In light of this, we measure and report a variety of equity and efficiency metrics for distinct sub-populations (average accessibility, fraction of origins above the median accessibility, and a metric relating to the objective function of our equity-driven optimization model) to give a more complete picture of the impact of network design decisions. We chose these metrics because they are interpretable and aligned with our optimization model objectives.

1.5 Case study: Toronto

We illustrate an accessibility-based cycling infrastructure optimization method using Toronto, Ontario, Canada as a case study. The City of Toronto, home to 2.8 million people in its current size and structure, was formed from the amalgamation of six smaller municipalities in 1998. Since then, transportation planning, design, construction, and political management has taken place on the scale of the amalgamated city, though political and infrastructure divides remain.

We compare a cycling network optimization for the entire city of Toronto with a combination of smaller optimized networks for each of the six pre-almagamation regions of Toronto which still carry political and cultural meaning in present-day Toronto [84, 85, 86]. The pre-amalgamation regions that lie on the outer edge of Toronto (Etobicoke, North York, and Scarborough) have large populations but very different cycling network characteristics from central Toronto. These areas generally lack on-road bicycle facilities but have many kilometres of off-road trails/paths. These regions are suburban with higher rates of marginalization and poverty than the City of Toronto as a whole [67, 87]: more than two-thirds of the

33 neighbourhoods identified as Neighbourhood Improvement Areas using a combination of measures of marginalization are in Etobicoke, North York, or Scarborough [88]. By explicitly studying these areas, we identify specific regional needs and differences that are not apparent on the scale of the entire city.

Municipal borders affect decision-making, political and societal perceptions of ownership and benefit, and data availability. By comparing optimization results from a single large region with diverse land-use and population characteristics with several smaller regions that are socially and historically meaningful, we highlight the impact of boundaries on network design decisions. Though the method we adapt has been constructed to achieve large speedups in processing time [21], a practical reason to consider smaller networks is to further speed up processing times [37] which affects downstream usability of the method. Our work highlights potential efficiency tradeoffs that may occur in such an approach.

2 Methods

2.1 Data

Our model calculated accessibility to jobs on low-stress roads and paths for each census dissemination area (DA) in Toronto, a metric that has been used by the City of Toronto to evaluate cycling infrastructure projects [16, 21] and is correlated with cycling mode choice [7]. We used the Level of Traffic Stress (LTS) network for Toronto produced by Chan *et al.* [21] with methods described in Lin *et al.* [7, 12]. An LTS rating of 1 through 4 was assigned to each road and path segment based on road geometry, vehicle speeds, and the presence and type of cycling infrastructure. We consider LTS 1 and LTS 2 low-stress and LTS 3 and LTS 4 high-stress, since the majority of the adult population is not comfortable cycling on LTS 3 and LTS 4 infrastructure [20]. We used the road network from July 2021.

We performed analysis using Toronto's 3702 census Dissemination Areas (DAs) [89] and job data per DA from the 2016 Canadian census [90]. We calculated accessibility to jobs per

	Model name	**Projects**	**Optimization goal**
1	Utilitarian model	High-stress arterial roads city-wide	Maximum accessibility to jobs city-wide
2a	Regional utilitarian model	High-stress arterial roads city-wide	Maximum accessibility to jobs for individual regions
2b	Regional utilitarian model	High-stress arterial roads within region	Maximum accessibility to jobs for individual regions
3	Equity-driven model	High-stress arterial roads city-wide	Maximum accessibility to lowest-accessibility DAs

Table 1: Model descriptions

origin as the total number of jobs in all DAs that can be reached from an origin DA within a 30-minute (7.5 km) bike ride using only LTS 1 and LTS 2 road and path segments. All LTS and accessibility data methods were as in Chan *et al.* [21].

We used the 2016 Ontario Marginalization Index [91] to assess the equity implications of bicycle infrastructure. We calculated Toronto-specific quintiles based on the DA-level factor scores for each of the four component dimensions (Residential Instability, Material Deprivation, Dependency, and Ethnic Concentration), then averaged the quintile scores to obtain an overall marginalization summary score for each DA [91]. A value of 1 indicates the least marginalized group and 5 indicates the most marginalized group.

2.2 Models

We explored three models of cycling network expansion: two based on a utilitarian goal to maximize accessibility to jobs, and one equity-driven sufficientarian model to maximize connections to regions with low accessibility (Table 1).

We used the optimization method developed by Chan *et al.* [21] to optimize cycling infrastructure for the entire City of Toronto (model 1, utilitarian model) and for each of the six pre-amalgamation regions of Toronto separately (model 2, regional utilitarian model). The objective of these models is to maximize the total accessibility of all DAs in the study area for a given budget in kilometres of new cycling infrastructure. In the equity-driven model (model 3) we adjusted the weighting of origin-destination (OD) pairs to prioritize destinations with low accessibility in the original network. These models are described in detail in the following sections.

In all three models, possible projects were defined as short (median length 1.2 km) sections of arterial road that are currently LTS 3 or LTS 4. For a given budget in kilometres of infrastructure, the combination of projects within the budget limit that maximized the objective function (total increase in accessibility for the utilitarian and regional utilitarian models or increase in connections to low-accessibility DAs for the equity-driven model) was selected.

We ran each model for total infrastructure budgets ranging from 30 km to 120 km in increments of 30 km. When results are presented for a single budget we used 90 km.

2.2.1 Model 1: utilitarian model

Model 1 solves a bilevel optimization for a cycling network design that maximizes accessibility to jobs on a network with LTS ≤ 2 for the entire City of Toronto. To overcome the computational challenge of solving over a million origin-destination (OD) routing problems for each potential network design, the model samples a subset of OD pairs and implements a machine-learning estimation method to approximate the impact of network design decisions on the unsampled pairs. For more details, see Chan *et al.* [21].

2.2.2 Model 2: regional utilitarian model

For a given budget for the entire city, we divided that budget by 6, allocating 1/6 of the total budget to each of the 6 pre-amalgamation regions. We then used the same optimization method as model 1 to maximize the total accessibility for DAs within each pre-amalgamation region. We chose an equal division of budget per region for simplicity and do not expect that other choices (such as allocating the budget proportional to population) will qualitatively affect our results.

The list of possible projects for model 2 was identical to that used for model 1: short sections of arterial road that are currently LTS 3 or LTS 4. For some budgets a greedy optimization method (sequentially selecting the single project that maximizes the accessibility increase until the budget is exhausted) performed better than the original optimization method, especially for small budgets (SI Figures 4-5). We retained the solution with the highest accessibility increase of the two methods for each budget.

We subsetted the city-wide list of projects in two possible ways for each region: either retaining the city-wide list of possible projects (model 2a, removing projects that were outside a 30-minute travel time from any origin in the region with a small buffer - these have no impact on accessibility within the region due to our choice of impedance function), or restricting projects to only those that are at least partially within the region (model 2b). The second is a more constrained optimization problem than the first. Infrastructure projects are highly political, and decision-makers tend to focus on whether projects take place within their local area or ward. We chose these two methods of allocating potential projects to highlight the impact of region-specific planning on where optimal infrastructure is located.

2.2.3 Model 3: equity-driven model

To prioritize network improvements for regions with low initial accessibility, we modified the weight applied to each origin-destination (OD) pair to be a function of the original job accessibility at the destination. In models 1 and 2, the OD pair weight q^{od} is simply the number of jobs at the destination. We modified the weight in the equity-driven model to instead give a weight between 0 and 1 based on the original total job accessibility of the destination a_0^d (equation 1):

$$q^{od} = 1 - \frac{a_0^d}{\max\, a_0^d} \tag{1}$$

The original total job accessibility a_0^d is the sum of all jobs in DAs that are reachable within 30 minutes of cycling at 15 km/h using only LTS 1 and LTS 2 roads and paths. In this formulation, $q^{od} = 1$ if the job accessibility at the destination is 0, and $q^{od} \approx 0$ if the job accessibility at the destination is close to the highest original job accessibility of any DA. This weighting scheme causes the model to value connections to DAs with low accessibility more highly than to DAs with high accessibility. There are many possible functional forms such a weight could take; we chose the form of equation (1) for simplicity and we do not expect other forms to make a qualitative difference in results. Note that this weight contains no information about the accessibility improvement gained by connecting an OD pair; a connection between two low-accessibility DAs is equivalent to a connection between one high-accessibility and one low-accessibility DA according to this weighting. Functionally this means that the model will prefer short connections in order to connect to as many low-accessibility DAs as possible within a given budget.

We considered only arterial roads as potential infrastructure projects as in models 1 and 2. Some DAs contain non-arterial high-stress roads, and the DA centroid node is sometimes mapped to a high-stress intersection. This means that for a subset of DAs that have zero initial job accessibility, there is no possibility to improve their accessibility with the project list we use. Of the 3702 DAs in Toronto, 1386 (37%) have zero accessibility to jobs under the current low-stress cycling network. Of these, 597 are not improvable under the chosen list of potential projects.

3 Results

3.1 Regional utilitarian and equity-driven optimizations lead to more spatially distributed infrastructure

Optimizing for the maximum increase in accessibility to jobs city-wide (model 1) led to proposed infrastructure that was clustered near downtown Toronto, the south-central area of the city (Figure 1, red, orange, purple, and black lines, SI Figure 6). This happened both because the density of jobs is highest near downtown (SI Figure 7), and because the cycling network and low-stress roads in general are more extensive near downtown (see

Figure 2D). These land use and infrastructure conditions combine to magnify the impacts of infrastructure changes in areas that are already well-connected [92, 12]. Note that due to data limitations we did not consider destinations outside the boundary of the City of Toronto; this also created a stronger pull towards the city centre than exists in reality, but this boundary is still quite far from where the resulting infrastructure projects are concentrated. In contrast, the combined optimal projects from each of the six pre-amalgamation regions (model 2) and the optimal projects from maximizing connections to DAs with low accessibility (model 3) resulted in network changes that were more spatially dispersed (Figure 1, yellow, blue, and green lines, SI Figures 8 and 9).

By prioritizing accessibility within each region individually, the regional utilitarian model (model 2) overcame some of the pull of downtown Toronto. Almost no potential projects were selected by multiple regions (SI Figure 8) – for the 90 km total budget shown in Figure 1, 3.4 km of projects were selected by multiple regions (SI Figure 10), indicating the strong dependence of the optimal projects on the area of interest. However, many projects selected by the utilitarian model (model 1) were also selected by the regional utilitarian model, particularly near downtown (see orange lines in Figure 1), which we expect for regions that are close to the downtown and also highly impactful in the city-wide model.

Though the equity-driven model (model 3) optimized only for connections to low-accessibility DAs regardless of the potential improvement in accessibility, infrastructure projects were still generally close to downtown. This may be both because DAs tend to be smaller and therefore closer together in more densely-populated areas and because the existing cycling network is more developed near downtown, meaning that a greater number of short connections were possible for a given budget if those connections were near downtown. Though downtown DAs tended to have higher initial accessibility to jobs (SI Figure 7), there were still many DAs with zero accessibility because their bounding roads were high-stress; these can be connected to the network with relatively short infrastructure projects.

We compared the results of the regional utilitarian model when projects were city-wide

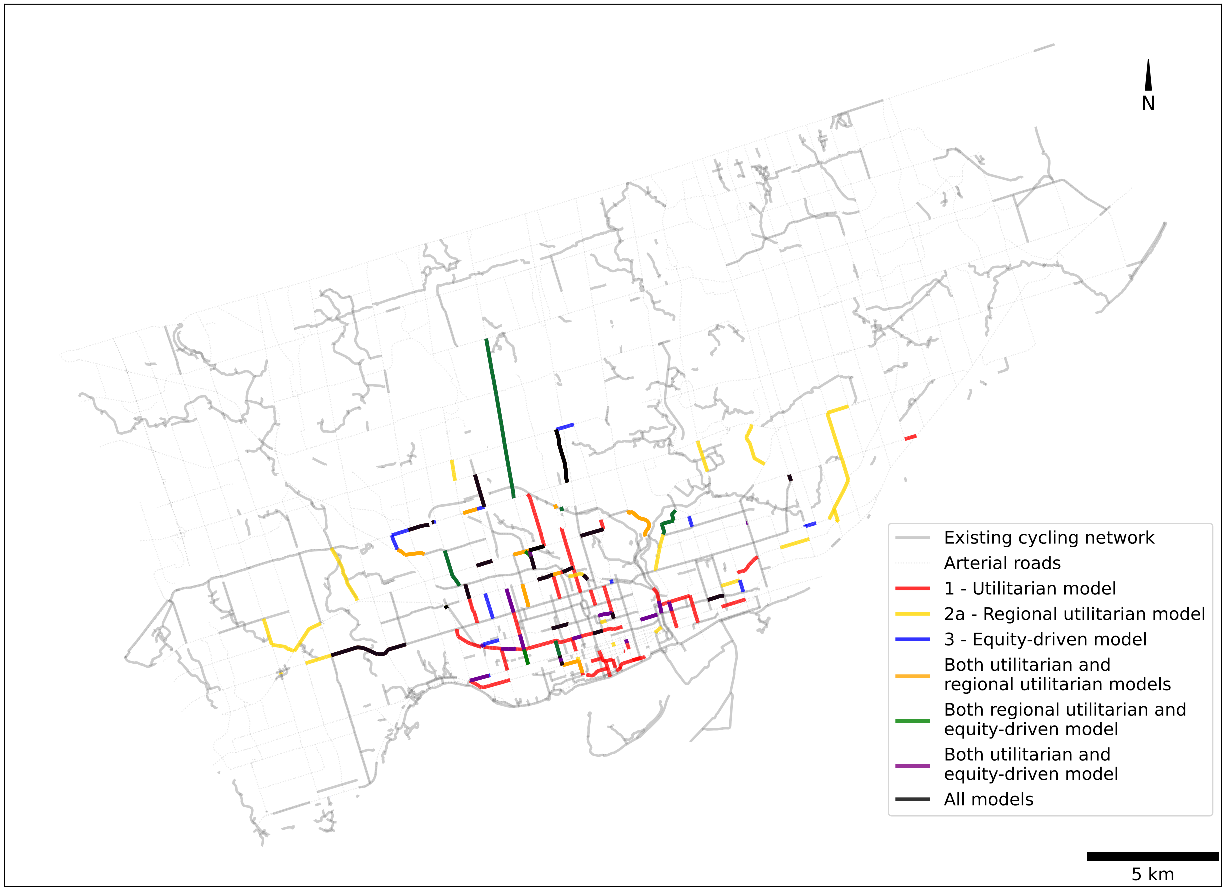

Figure 1: **Regional utilitarian and equity-driven optimizations lead to more spatially distributed infrastructure than a pure utilitarian model**. Comparison of all three models in Toronto: utilitarian model (model 1, red), regional utilitarian model (model 2a, yellow) and equity-driven model (model 3, blue) for a total budget of 90 km. Segments where model solutions overlap are shown in secondary colours (orange, green, purple, and black). Arterial roads are shown as thin dashed grey lines and the original cycling network from October 2021 (multi-use trails, contraflow lanes, cycle tracks, and bike lanes, with sharrows and suggested routes omitted) is shown in thick grey lines. In the regional utilitarian model, projects are city-wide and not restricted to each region (model 2a), and accessibility to jobs is maximized for origins within each region.

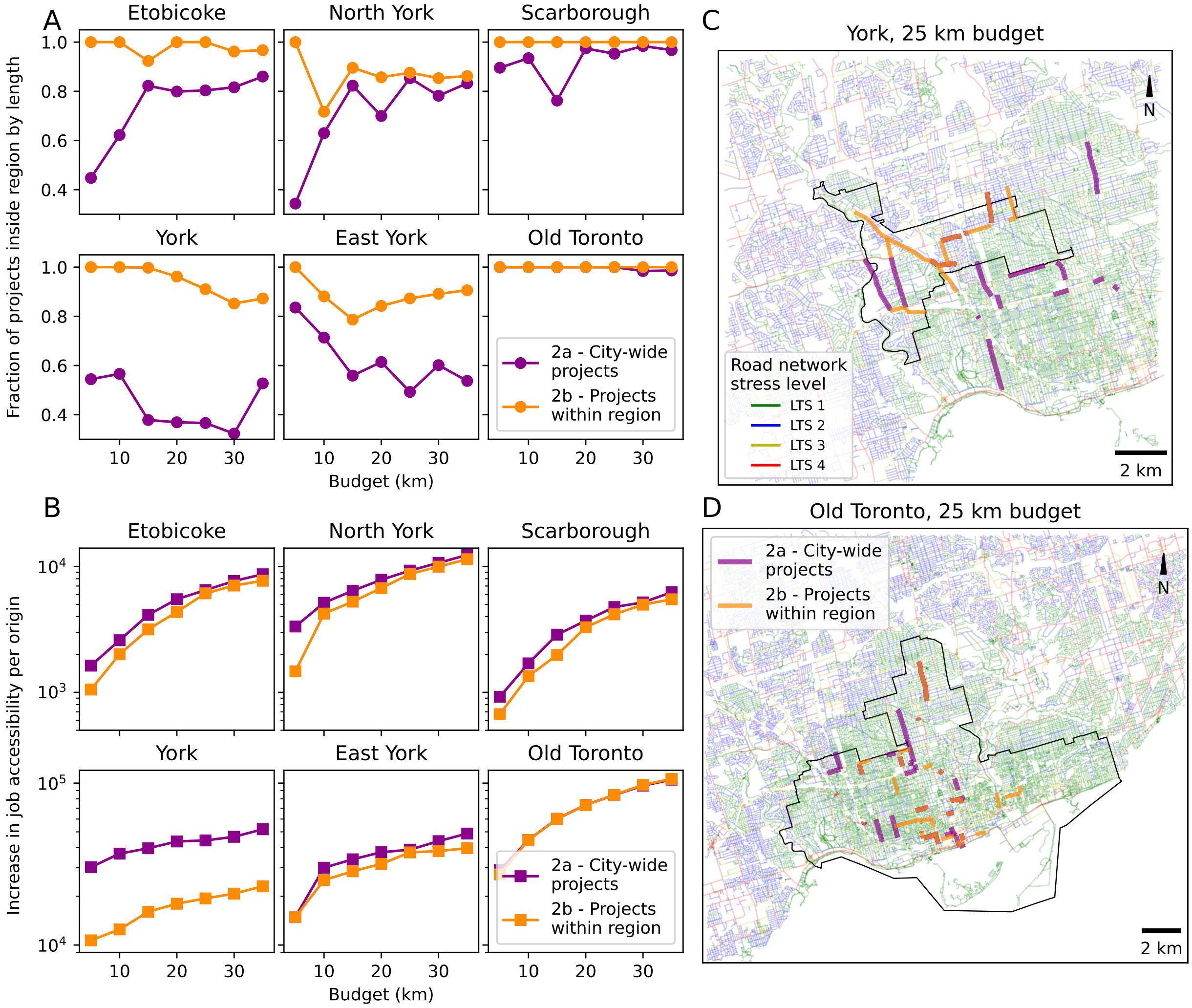

Figure 2: **Model 2: optimal infrastructure may be located outside a region**. (A) The fraction of optimal projects that maximize accessibility for origins in each region when the project list is restricted to the region (model 2b, orange) or is city-wide (model 2a, purple). Some project edges are located outside the region even in the first case because the project crosses the region boundary. (B) The average increase in accessibility to jobs per origin for each region when the project list is restricted to the region (orange) or is city-wide (purple). (C-D) Maps for York (C) and Old Toronto (D) showing the optimal infrastructure locations when projects are restricted to the region (model 2b, orange) or are city-wide (model 2a, purple). The original LTS level for each segment is plotted on each map.

(model 2a) or restricted to each region (model 2b). We found in model 2a that some of the optimal projects for a region were located outside that region, both because of peoples' ability to travel to destinations outside the region and their ability to choose low-stress routes outside the boundary to destinations within the region. This was true for all regions except Old Toronto (Figure 2A,C-D). The length of optimal projects that fell outside the region was largest for York and East York, two small regions that border downtown Toronto (Figure 2A,C) – their accessibility gains were largest when they could more easily connect to the destinations and infrastructure in downtown Toronto. In contrast, even when free to choose projects outside its boundaries, Old Toronto benefited most from projects inside the region (Figure 2D). Finding optimal infrastructure for a region outside its boundaries challenges political perceptions of who infrastructure is for, highlights the functional connections between adjacent regions in large metropolitan areas, and challenges the usefulness of proximity-based measures of infrastructure benefits.

3.2 The most and least marginalized groups benefit differently from each optimization strategy

The utilitarian and regional utilitarian models optimized for the total increase in accessibility to jobs, a utilitarian metric, while the equity-driven model prioritized connections to low-accessibility DAs, encoding a sufficientarian approach to accessibility. We measured each model's results by these two objective functions and found that the utilitarian model performed best of all the models by its own optimization goal and likewise the equity-driven model performed best when all models were evaluated based on its objective function, as one would expect (Figure 3A). The objective function for the utilitarian models is a measure of the overall efficiency of the solution — the total increase in accessibility to jobs. On the other hand, the objective function for the equity-driven model is a measure of both connectedness and the original accessibility of connected pairs.

More spatially extensive infrastructure came at a cost in overall accessibility for both the regional utilitarian and equity-driven models compared to the utilitarian model (Figure 3, SI Figure 11). The total increase in accessibility was lower in the regional utilitarian model because optimizing for pre-amalgamation regions is a more constrained optimization problem than the pure utilitarian model. For the equity-driven model, not having the explicit goal of maximizing accessibility also led to a smaller total increase in accessibility. With a 90 km city-wide budget (15 km per region), each DA in the regional utilitarian model experiences an average increase in job accessibility of 23,964 when projects are limited to each region (model 2b) and 27,811 when projects are city-wide (model 2a). Each region individually also experiences larger accessibility increases when projects are not constrained to the region in the regional utilitarian model (Figure 2B). The equity-driven model gives an average increase in job accessibility per DA of 28,859. In contrast, the utilitarian model results in an average increase of 44,032 accessible jobs per DA (SI Figure 11), a 71% increase from the original average accessibility of 61,954 jobs per DA.

Building on work that suggests setting a minimum accessibility threshold is more equitable than providing the highest utilitarian accessibility [46, 45], we asked how each model impacted DAs with a high or low Marginalization Index [91]. For all but the highest levels of accessibility to destinations, more marginalized areas tended to have lower access before optimization (SI Figure 12), and these areas continued to have lower overall accessibility after optimization (Figure 3).

We compared the final mean job accessibility per DA and the fraction of DAs above the original median accessibility for each model, effectively choosing the median as a sufficientarian threshold of accessibility. Because the distribution of accessibility is so broad both before and after optimization, the mean accessibility is highly influenced by the top end of the distribution and the median is more reflective of typical accessibility. For a 90 km budget and for the most marginalized 40% of DAs (quintiles 4 and 5), the equity-driven model brought more DAs above the median than the other models, but the utilitarian model led to the highest mean job accessibility, indicating an equity-efficiency tradeoff for this group

(Figure 3B, dotted line). However, for the least marginalized (most privileged) 40% of DAs, the utilitarian model brought more DAs above the original median accessibility while also giving the largest increase to the mean accessibility, implying no tradeoff between equity and efficiency for this group (Figure 3B, dash-dotted line). These trends depended on the total infrastructure budget: in general, the equity-driven model brought more DAs over the pre-optimization median accessibility relative to the other models as the infrastructure budget increased (SI Figures 13 and 14). This indicates synergistic equity benefits at larger budgets in comparison to the utilitarian models.

These results show that each optimization model has diverging impacts on subsets of the population and that aggregate measures across the entire population hide these contrasting impacts on different groups. This has equity implications in our results. Focusing on the doubly-disadvantaged DAs that are both marginalized and have low accessibility highlights a different 'optimal' strategy than for the population as a whole, even when an equity-type metric such as the fraction of DAs above the median is used for the population as a whole. We find that with utilitarian optimization the rich get richer. Decision-makers must be very clear who is intended to benefit and why in order to properly design and prioritize infrastructure changes. This can also inform their subsequent tolerance for usage rates in new infrastructure, as new infrastructure in lower accessibility areas will see lower ridership until the overall accessibility is increased [7].

4 Discussion

In principle, providing equitable and efficient access to destinations on safe cycling routes could be easily achieved with a large infrastructure budget. However, even in the case of a very large budget and ambitious network plan, functional constraints on workers, equipment, and level of disruption will limit how fast cities can improve their low-stress cycling network in the short term. Prioritization of infrastructure will always be necessary. Even if all the

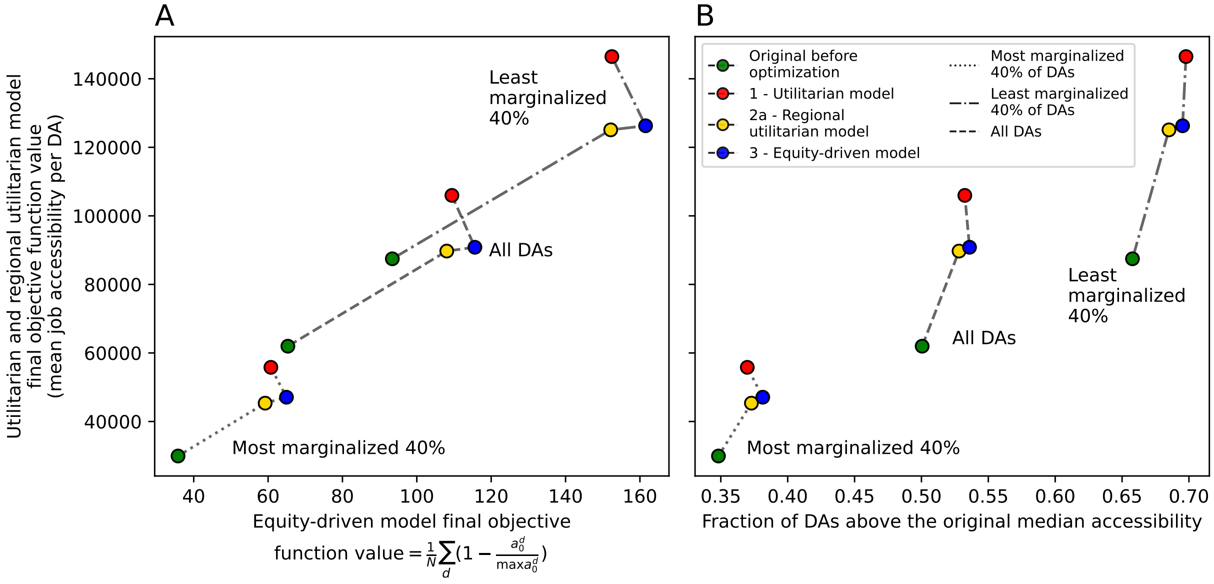

Figure 3: **Utilitarian and equity-focused metrics reveal diverging impacts on the most and least marginalized areas (90 km budget).** (A) Objective function weights for the utilitarian (model 1) and regional utilitarian (model 2a) models vs. objective function weight for the equity-driven model (model 3) for three groups of DAs: the 40% most marginalized DAs by average Marginalization Index quintile, the 40% least marginalized DAs, and all DAs. The utilitarian model objective can be summarized as the mean final accessibility to jobs per DA. The equity-driven model objective is the average sum of accessibility weights for reachable DAs. (B) Mean final accessibility to jobs per DA vs. the fraction of DAs in each group that are above the original city-wide median accessibility.

options being considered will eventually be realized, there are still impacts to choosing one build-out strategy over another. The need to make decisions along a spectrum of utilitarian benefit and equity will always be present, and the advantage of optimization is the efficient deployment of infrastructure towards a goal.

We show in this work that choices made in the optimization process about problem constraints, optimization area, and optimization metric have profound impacts on the "optimal" infrastructure projects for improving accessibility to destinations. Decision-makers and planners must be clear on the goals they are trying to achieve and what tradeoffs are acceptable to reach them.

We found that the infrastructure projects that most improved cycling accessibility to destinations for a region were often located outside that region, especially for non-central areas of Toronto. This stands in direct contrast to the majority of existing work using equity to rank infrastructure projects which "equat[es] proximity and impact" [82]. Our results highlight the importance of looking beyond proximity to consider routes and accessibility to destinations when understanding the equity impacts of infrastructure. Accounting for the function of a transportation system is even more important in the case of cycling than for walking or public transit. Walking is slow compared to other methods of travel, and hence spatial proximity may be a reasonable measure of value. Public transit networks are continuous by definition given that routes must start and end at hub locations, and so being able to access a transit stop can reasonably be assumed to give access to the network (though there are important costs and barriers associated with the number of transfers needed). In contrast, cycling networks are very frequently discontinuous and so access to a particular piece of infrastructure is not consistently predictive of access to destinations.

In our results, optimizing over smaller regions (model 2) or optimizing for minimum accessibility (model 3) resulted in a lower overall accessibility than a utilitarian optimization that maximized the highest overall accessibility (model 1). These results are an example of an equity-efficiency tradeoff. A fixed infrastructure budget means that choosing to build infrastructure in one place prevents it from being built somewhere else, so there are always tradeoffs present in who will benefit and by how much. However, we found that the city-wide utilitarian optimization (model 1) benefited the least-marginalized (most privileged) 40% of DAs most, both in their final average accessibility and in the number of DAs above the original median accessibility (Figure 3B), implying that equity-efficiency tradeoffs may be more or less severe for particular sub-groups and sub-regions of the city.

There is likely a functional sufficient threshold for the amount of accessibility that an individual or region needs to meet all their needs, to have a good quality of life, or to achieve some other metric of sufficiency [93]. If there is such a bound, then improvements for areas with high access may have only a small impact on functional accessibility. By prioritizing bringing areas up to the sufficient threshold of accessibility, it may then be possible to improve things for people with less access without a tradeoff for areas with high access. If someone can access thirty grocery stores, the impact of being able to access thirty-one could reasonably be assumed to be lower than the impact of going from access to no grocery stores to one, or even one to two [45]. While it takes more infrastructure to increase accessibility by a smaller amount in areas where accessibility is currently low, the impact of small accessibility changes can be larger in areas where accessibility is currently low as long as they pass a threshold of providing meaningful function.

Measuring and evaluating accessibility must also take into account the real accessibility needs of individuals, and recent work towards sufficiency standards of accessibility will greatly help [50, 46]. For instance, Martens *et al.* set a sufficiency threshold for public transit as a fraction of the average car-based accessibility for a region [50], and Allen and Farber found "participation deserts" in Toronto where participation in activities was lower than expected and correlated with low accessibility to destinations by transit [46]. Though sufficient thresholds of accessibility have not been clearly defined (and may be impossible to define in general), we find that considering an explicit threshold of accessibility and evaluating the threshold for individual regions avoids the pitfalls of group averages [50] by treating the needs of individuals as distinct from the group.

Measuring accessibility to destinations highlights the relationship between land use and transportation. Neither exists without the other, both in terms of short-term changes to accessibility and longer-term development and planning practices. Cities seeking to improve accessibility to destinations can do so by improving transportation infrastructure, by intensifying land use in target areas, or both [46].

5 Conclusion

In this work, we compared three optimization methods for improving accessibility to destinations on a low-stress cycling network in Toronto. We showed that model choices about spatial resolution and region of interest meaningfully impacted model outcomes with the largest average accessibility increases when the largest possible region was considered as a unit. Overall accessibility increases came at an equity cost, however: the city-wide utilitarian optimization favoured infrastructure near downtown in areas that already have high accessibility. In contrast, optimizing infrastructure in Toronto's pre-amalgamation regions individually produced lower total accessibility gains but more spatially distributed infrastructure, and optimizing for connections to low-accessibility DAs in an equity-driven model led to more DAs above the original median accessibility.

When we considered destinations and infrastructure outside of a region as part of its optimization, we found that the projects that most improved the region's accessibility were frequently not located in the region itself. This challenges the common understanding that people are impacted most by features of their physical environment that are close to them.

Accessibility to destinations is extremely non-uniform in Toronto, both spatially and socio-demographically. We showed that the most marginalized 40% of DAs in Toronto experienced the lowest levels of accessibility to destinations both before and after infrastructure optimization regardless of the optimization model used. However, we found contradictory impacts on equity depending on the population subset considered, with the equity-driven model having a larger impact on the most marginalized DAs than the other two models but the utilitarian model benefiting the least-marginalized (most privileged) DAs more than the other models. We expect similar trends in other cities that also show pattern of more robust cycling infrastructure in areas that include both destinations of interest and relatively fewer marginalized people.

6 Author contributions

Madeleine Bonsma-Fisher: Conceptualization, Methodology, Software, Investigation, Visualization, Writing - Original Draft. Bo Lin: Methodology, Software, Writing - Review & Editing. Timothy Chan: Conceptualization, Methodology, Supervision, Writing - Review & Editing. Shoshanna Saxe: Conceptualization, Methodology, Supervision, Funding Acquisition, Writing - Review & Editing.

7 Acknowledgements

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8 Supplementary Information

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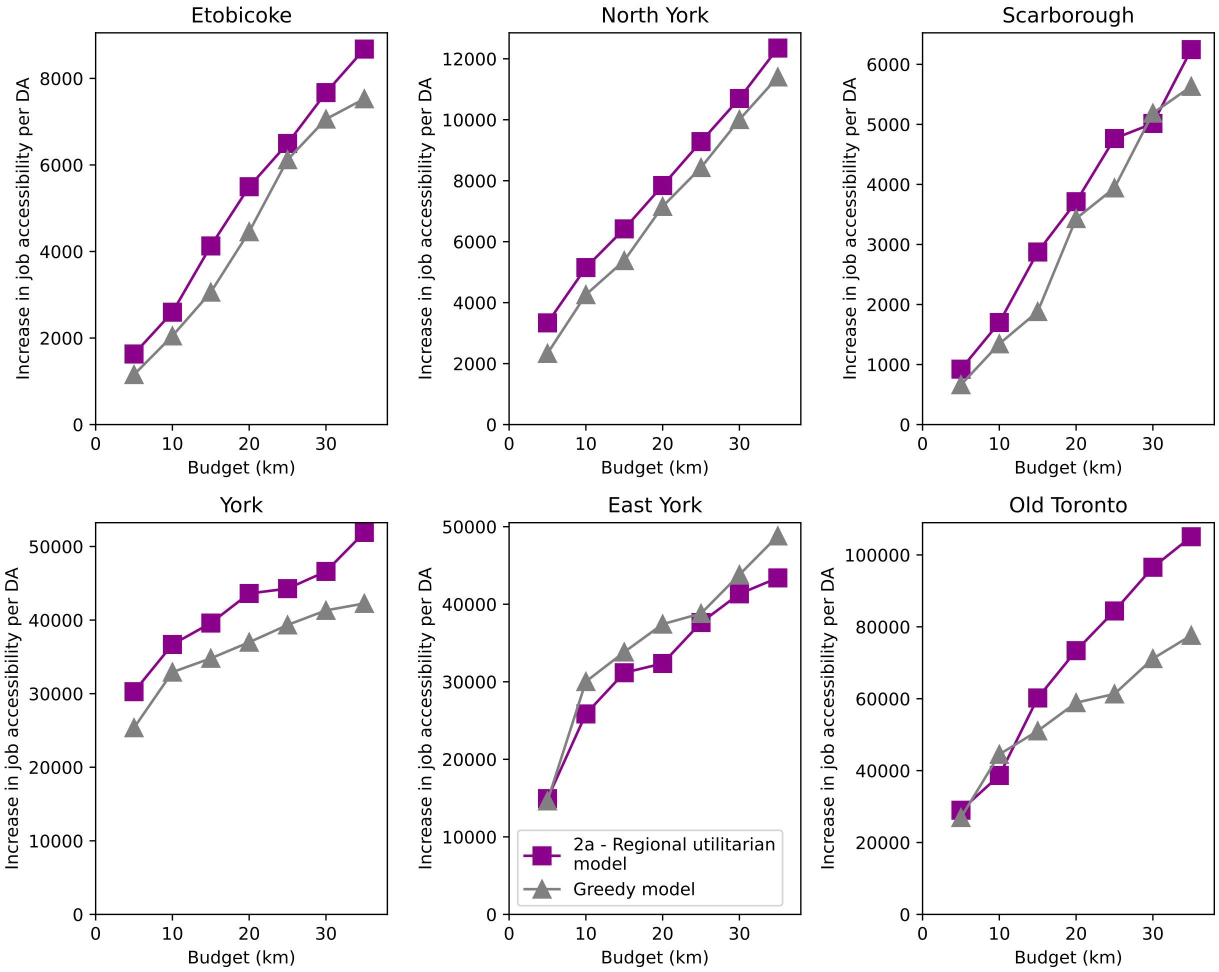

Figure 4: Average accessibility increase per DA for each pre-amalgamation region with projects allowed to be city-wide (model 2a) using either a greedy method (grey) or the regional utilitarian optimization model (purple).

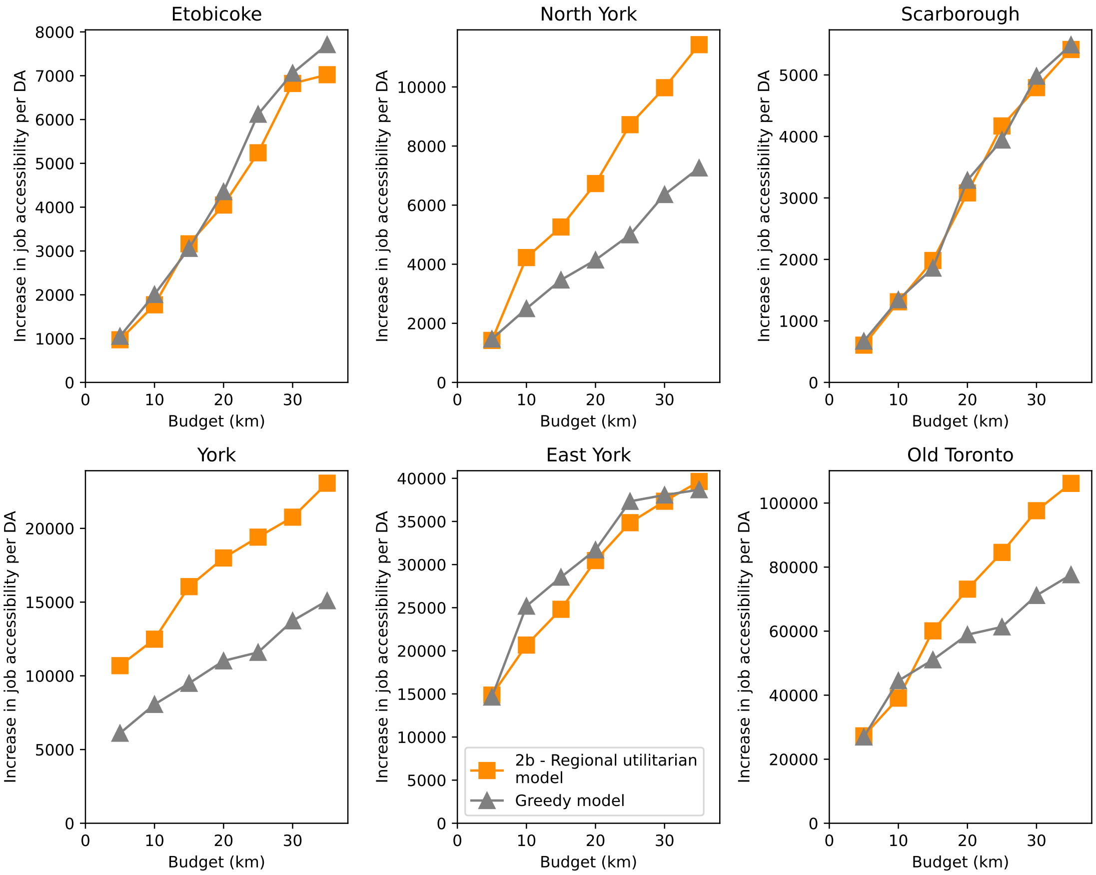

Figure 5: Average accessibility increase per DA for each pre-amalgamation region with projects limited to each region (model 2b) using either a greedy method (grey) or the regional utilitarian optimization model (orange).

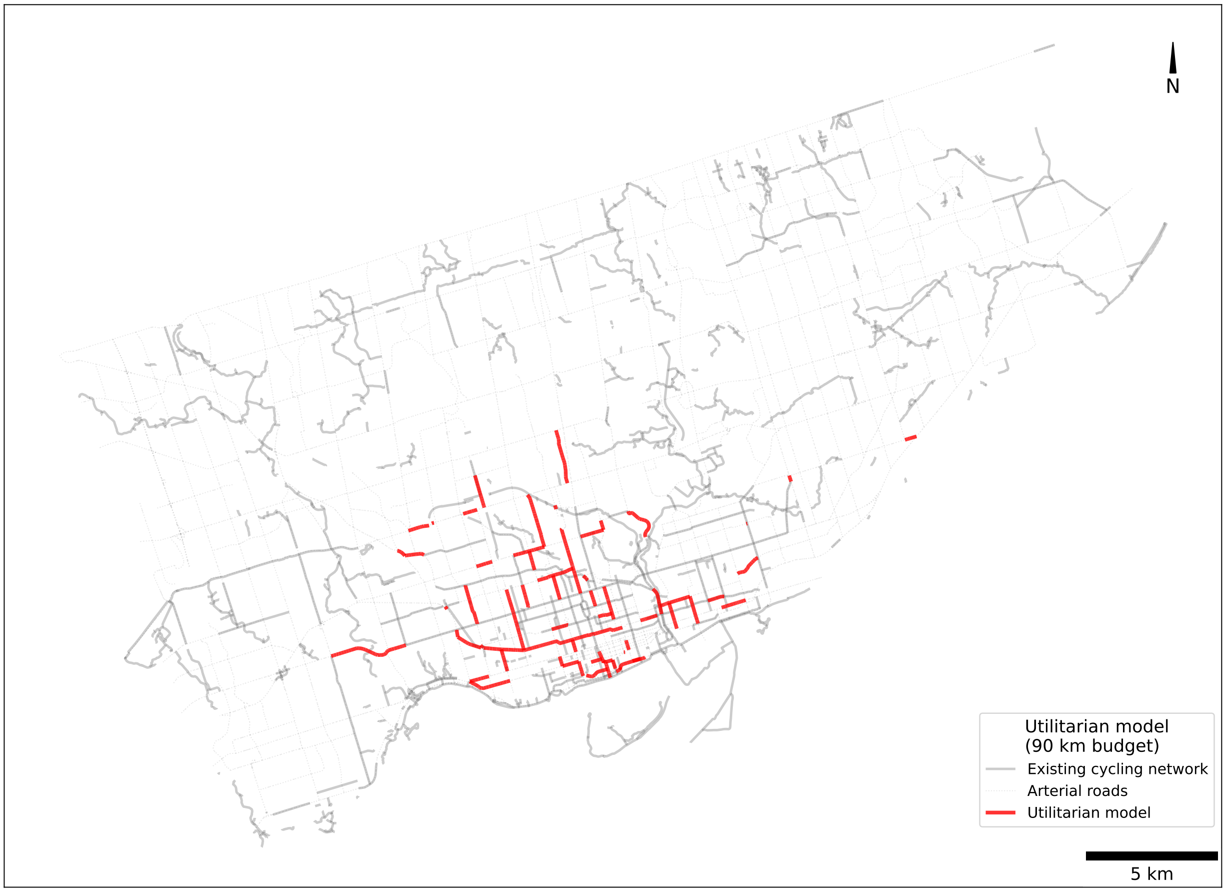

Figure 6: Utilitarian model optimal projects (model 1, red) for a total budget of 90 km. Arterial roads are shown as thin dashed grey lines and the original cycling network from October 2021 (multi-use trails, contraflow lanes, cycle tracks, and bike lanes, with sharrows and suggested routes omitted) is shown in thick grey lines.

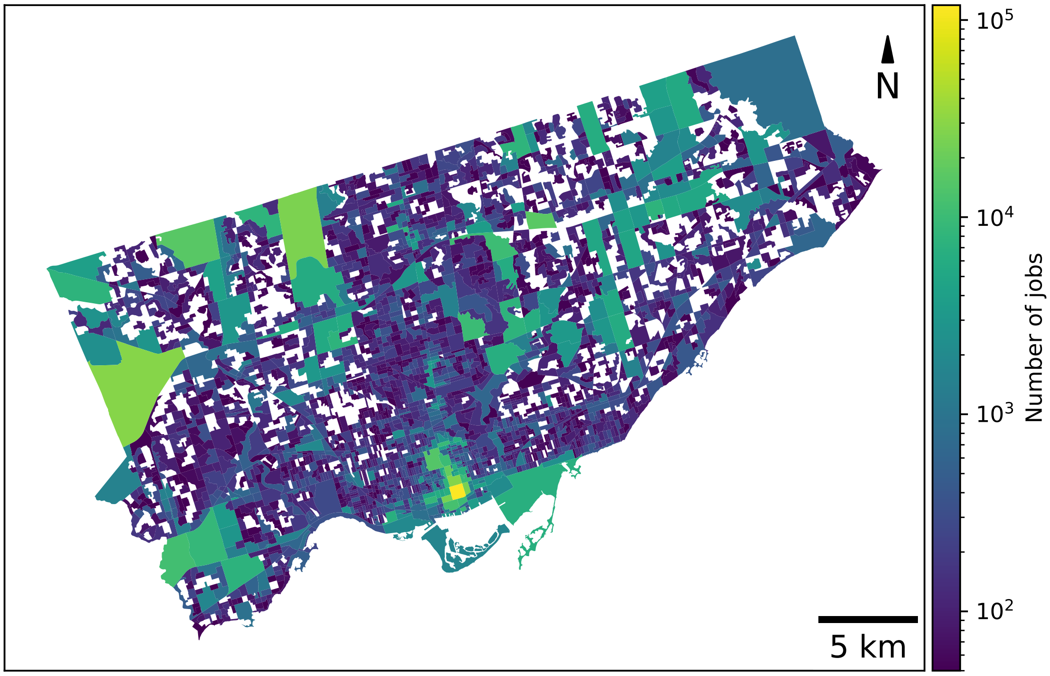

Figure 7: Number of jobs per DA in Toronto from 2016 census data. DAs with fewer than 50 jobs are shown at the darkest purple colour level; DAs with zero jobs are in white.

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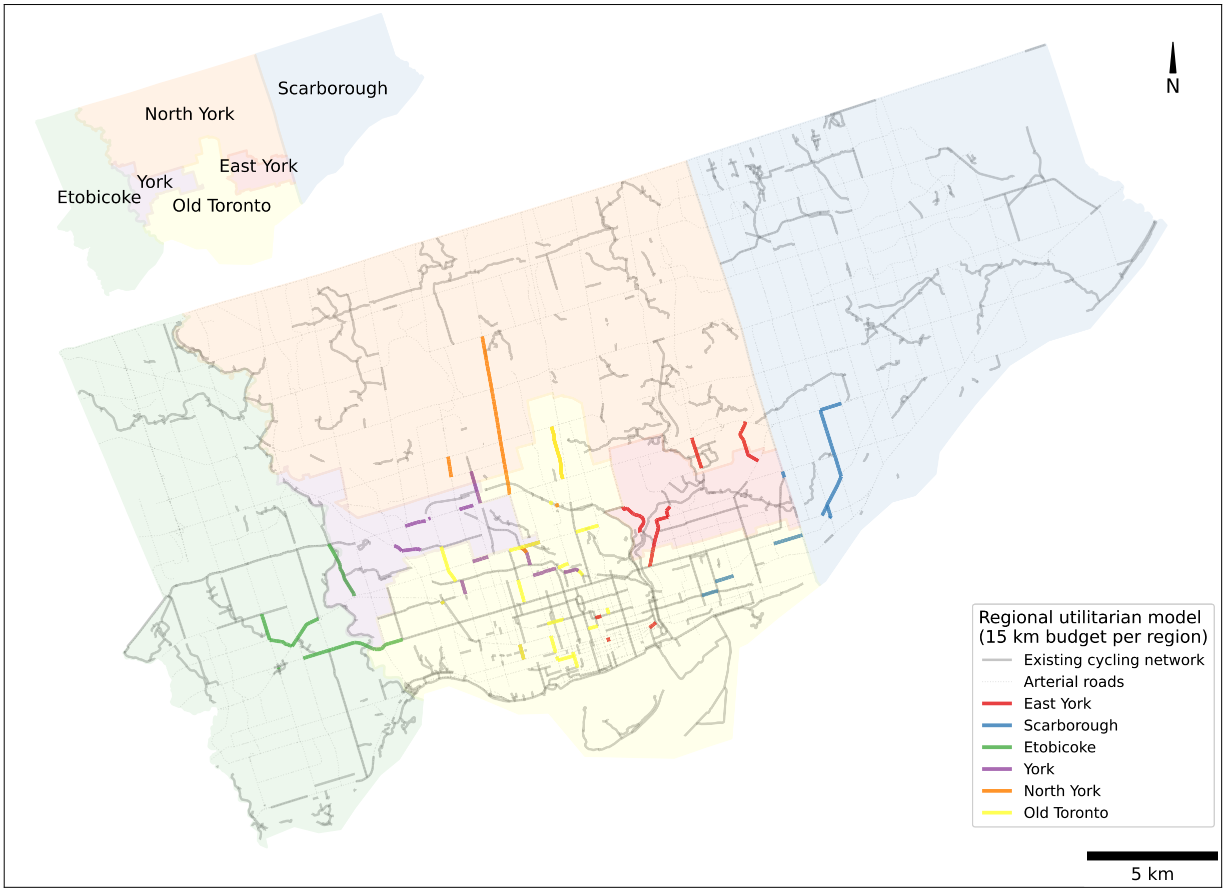

Figure 8: Regional utilitarian model optimal projects (model 2a, coloured by region) for a total budget of 90 km. Arterial roads are shown as thin dashed grey lines and the original cycling network from October 2021 (multi-use trails, contraflow lanes, cycle tracks, and bike lanes, with sharrows and suggested routes omitted) is shown in thick grey lines.

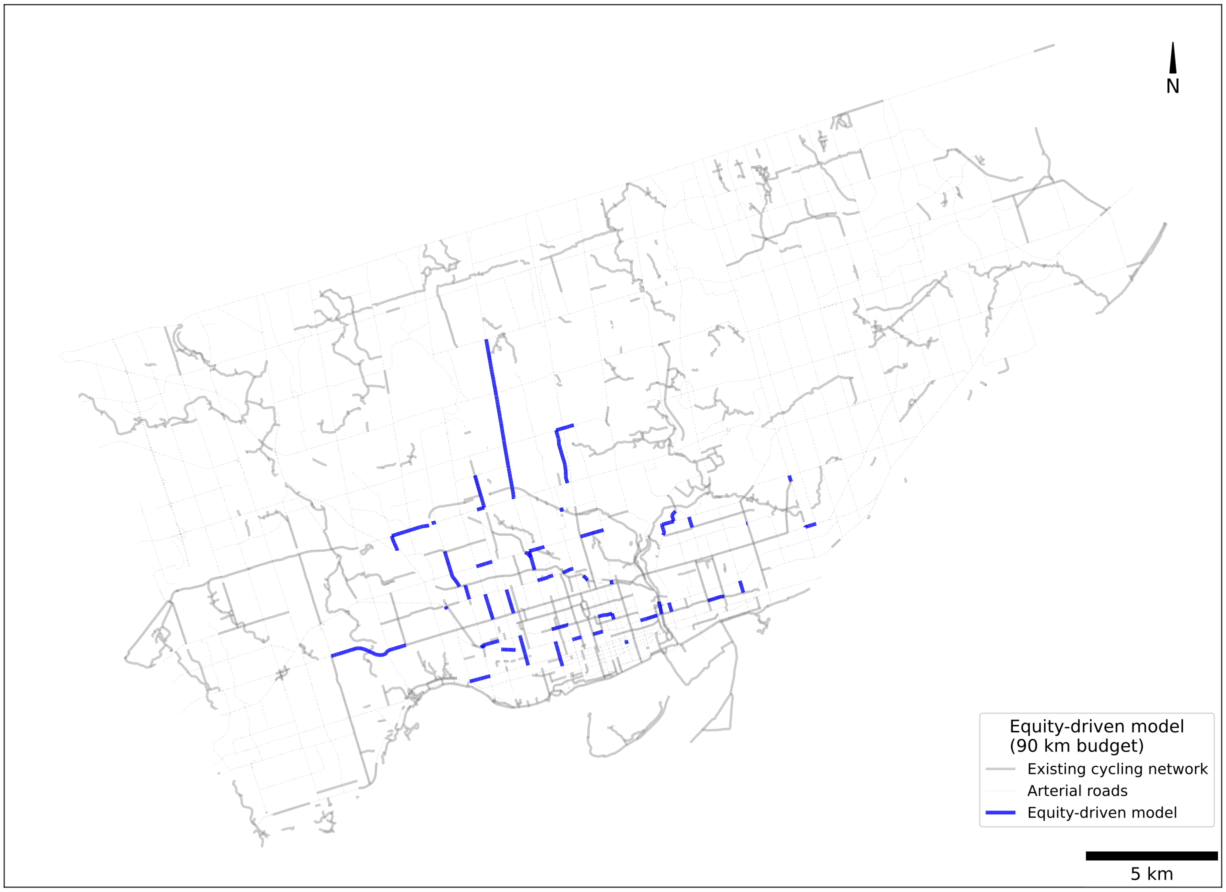

Figure 9: Equity-driven model optimal projects (model 3, blue) for a total budget of 90 km. Arterial roads are shown as thin dashed grey lines and the original cycling network from October 2021 (multi-use trails, contraflow lanes, cycle tracks, and bike lanes, with sharrows and suggested routes omitted) is shown in thick grey lines.

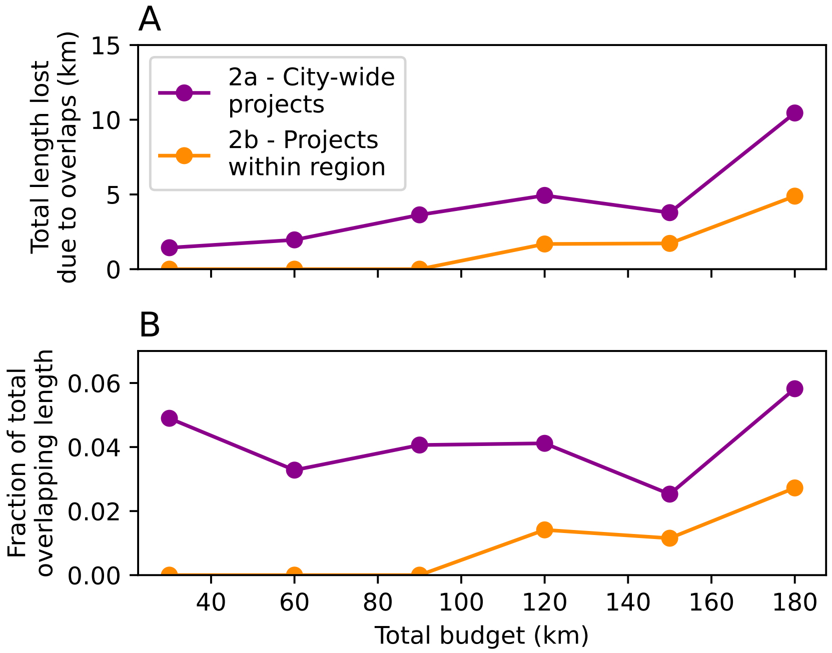

Figure 10: (A) Length difference between sum of project lengths for each individual region and the sum of the combined unique projects from all regions when the project list is restricted to the region (model 2b, orange) or is city-wide (model 2a, purple). (B) Fraction of city-wide project budget represented by the overlapping project lengths in (A).

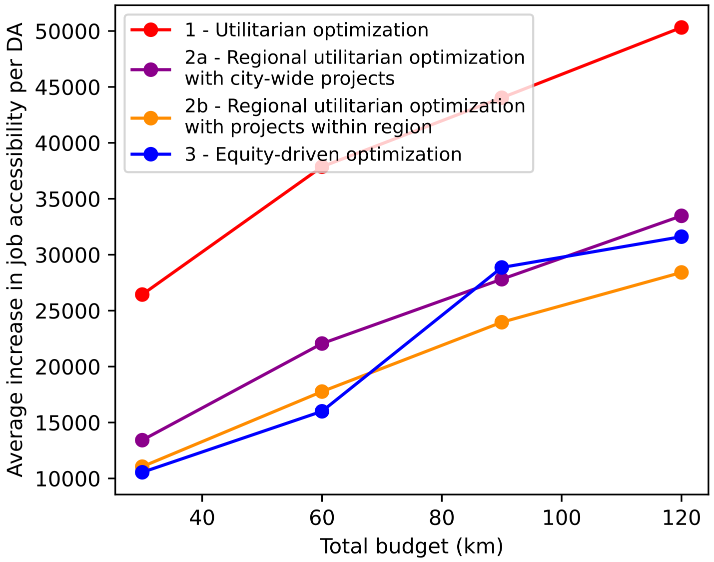

Figure 11: Average increase in job accessibility per origin for each optimization method used. The best result of 21 random seeds was used for each model; for models 1 and 2 this is measured in terms of the total accessibility increase and for model 3 this is measured using its own objective function (maximizing connections to low-accessibility DAs).

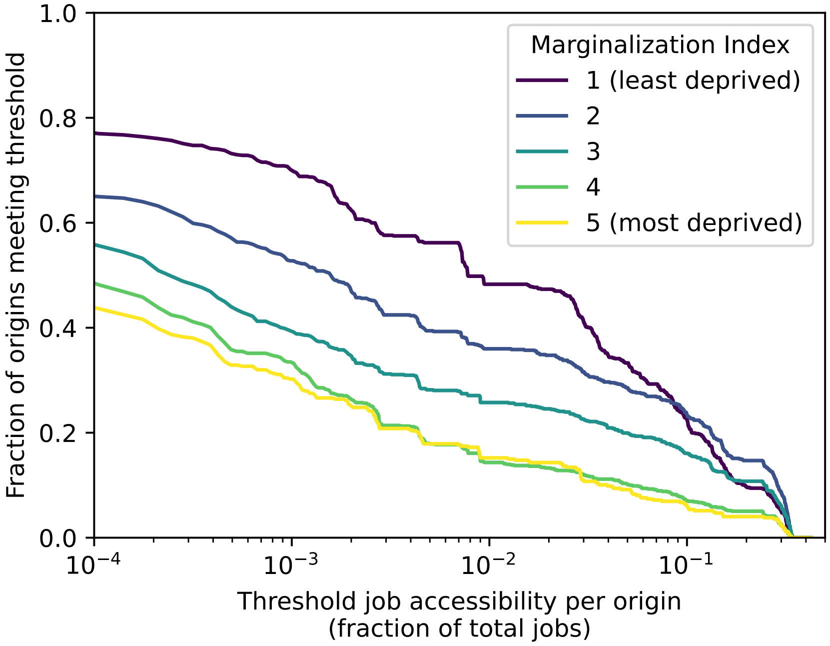

Figure 12: Fraction of origin DAs meeting an accessibility threshold grouped by Marginalization Index quintiles.

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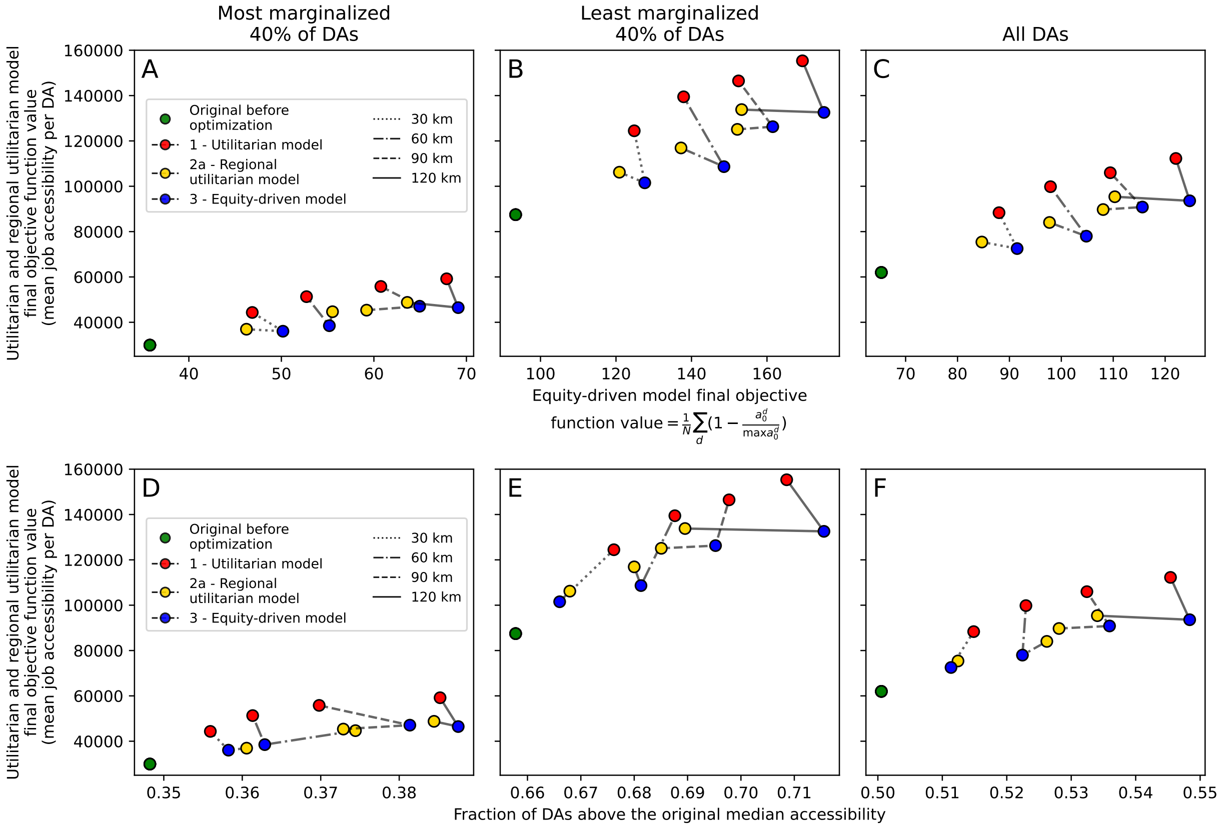

Figure 13: **Utilitarian and equity-focused metrics reveal diverging impacts on the most and least marginalized areas.** (A-C) Mean accessibility to jobs vs. objective function value for equity-driven model per DA for the 40% most marginalized DAs by average marginalization index quintile (A), the 40% least marginalized DAs (B) and all DAs (C). (D-F) Mean accessibility to jobs per DA vs. the number of DAs that are above the original median accessibility to jobs for the 40% most marginalized DAs (D), the 40% least marginalized DAs (E) and all DAs (F). In all plots line dash type indicates the total infrastructure budget and marker colour indicates the starting condition (green) and each of the optimization models (red, yellow, blue).

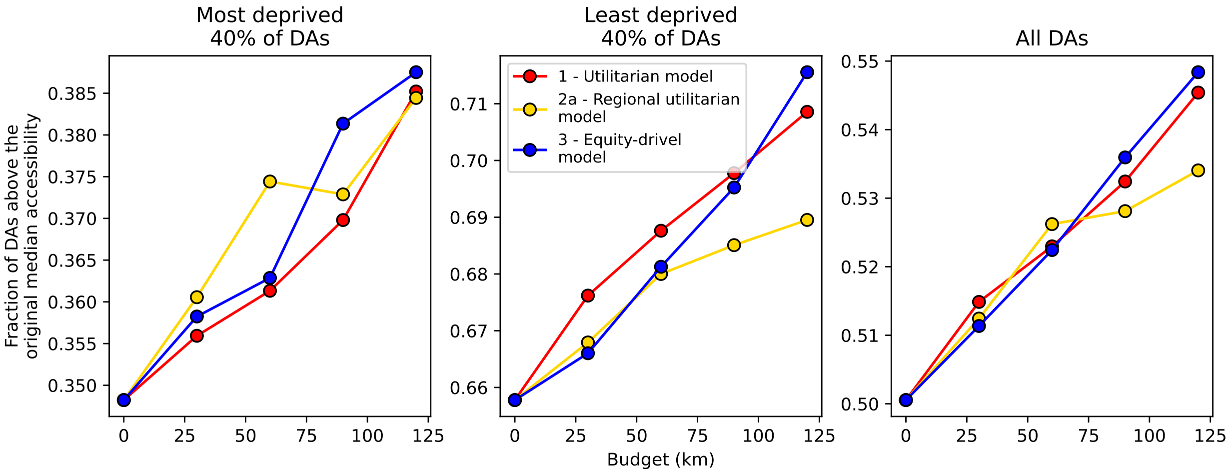

Figure 14: The fraction of DAs above the original median accessibility to jobs for the 40% most marginalized DAs (left), the 40% least marginalized DAs (centre) and all DAs (right). In all plots marker colour indicates each of the optimization models (red, yellow, blue).

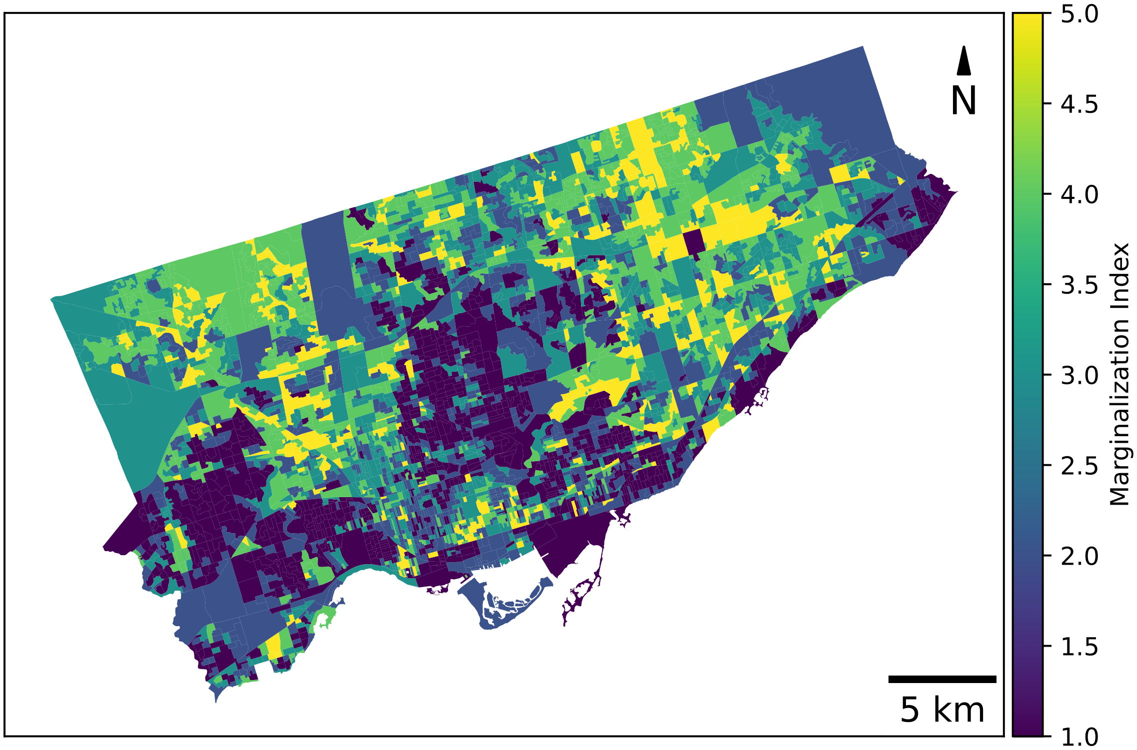

Figure 15: Marginalization Index quintiles for all DAs in Toronto. A high marginalization index represents more deprived areas.

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