My title*

My subtitle

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My abstract

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*Code and data are available at: https://github.com/iJustinn/Toronto_Cycling_Network

1 Introduction

You can and should cross-reference sections and sub-sections. We use R Core Team (2023).

The remainder of this paper is structured as follows.

2 Data

2.1 Source

The data used in this paper was collected by the OpenDataToronto Library (Gelfand 2020). OpenDataToronto provides a platform for the public to access various datasets related to Toronto's civic operations and urban infrastructure. The specific dataset used in this research is the 'Cycling Network' (Data 2024), which provides detailed information on Toronto's bicycle infrastructure, including dedicated lanes, multi-use trails, and shared roadways. This dataset plays a crucial role in promoting active transportation and urban sustainability efforts within the city. It is frequently updated to reflect ongoing expansions and modifications to the cycling infrastructure, aligning with Toronto's broader efforts to reduce congestion, enhance mobility, and support environmental goals. This dataset not only informs local decisions but also contributes to broader discussions on urban transportation planning and sustainability in growing cities around the world.

Data used in this paper was downloaded, cleaned and analyzed with the programming language R (R Core Team 2023). Also with support of additional packages which will be talked about in the Section 2.3.

2.2 Measurement

The 'Cycling Network' dataset from Open Data Toronto tracks various aspects of Toronto's cycling infrastructure, such as installation dates, upgrades, street names, and the type of infrastructure (e.g., sharrows, multi-use trails). Each entry represents a segment of the cycling network, where real-world phenomena, such as the construction or upgrading of cycling paths, are documented. For example, when a cycling path is installed or upgraded, the responsible authorities collect information such as the installation year (e.g., 2001) and any subsequent upgrades (e.g., 2021). This data is then digitized into structured entries in the dataset.

To go from a physical event (e.g., the installation of a bike lane) to a dataset entry, detailed records are maintained by the city's transportation department. These records are geospatially coded (column geometry in this dataset), allowing each cycling path to be mapped precisely in relation to other city infrastructure. Thus, the phenomena of constructing or updating a bike lane becomes an entry with attributes such as the street name, road class, and installation

Table 1: Raw Coordinates

Simplified Geometry
{'type': 'MultiLineString', 'coordinates': [[[-79.4035069136297, 43.6952595244941], [-79.403
{'type': 'MultiLineString', 'coordinates': [[[-79.4036386937994, 43.6349938275931], [-79.403
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{'type': 'MultiLineString', 'coordinates': [[[-79.5430542283657, 43.58695658908], [-79.54307

Table 2: Extracted and Cleaned Coordinates

Longitude	Latitude	ID
-79.40351	43.69526	1
-79.40309	43.69535	1
-79.40240	43.69549	1
-79.40364	43.63499	2
-79.40355	43.63519	2
-79.40346	43.63535	2

history. This allows researchers to analyze trends in cycling infrastructure and its expansion over time.

2.3 Method

Data used in this paper was cleaned, processed, modeled and tested with the programming language R (R Core Team 2023). Also with support of additional packages in R: `sf` [], `readr` (Wickham, Hester, and Bryan 2023), `ggplot2` (Wickham 2016), `osmdata` [], `tidyverse` (Wickham et al. 2019), `jsonlite` [], `dplyr` (Wickham et al. 2023), `here` [], `knitr` [], `kableExtra` [], `[],` [], .

In the first data cleaning process, the focus was on extracting and cleaning geographical coordinates from the 'geometry' column, which contains location data in JSON-like format, Table 1 displays how the data was like. A custom function was created to parse the coordinates, filter out invalid entries, and extract the longitude and latitude values. The extracted coordinates were combined into a new dataset shon in Table 2, with unique IDs to match the original entries. Any rows with missing coordinate data were removed, and the cleaned data was saved into a separate file for further analysis.

The second cleaning process dealt with the 'UPGRADED' column, which contains information

Table 3: Number of Lane Upgrades by Year

Year	Number of Upgraded Lanes
2018	9
2019	14
2020	46
2021	28
2022	15
2023	12

Table 4: Number of Bikeways Installed by Year

Year	Number of Installed Bikeways
2001	539
2002	12
2003	15
2004	20
2005	65
2006	75

about the years when cycling lanes were upgraded. Invalid or missing years were filtered out, and the remaining valid data was converted to a numeric format. The dataset was then grouped by the year of upgrade, with a summary created to count the number of lanes upgraded in each year. This summarized data, Table 3, was saved for use in analyzing trends in lane upgrades over time.

In the third cleaning process, the focus was on the 'INSTALLED' column, which records the years when cycling infrastructure was first installed. Similar to the 'UPGRADED' column, invalid or missing years were removed, and the data was converted to numeric format. The installation data was grouped by year to count the number of bikeways installed each year. The resulting summary, Table 4, was saved for further trend analysis on the growth of the cycling network.

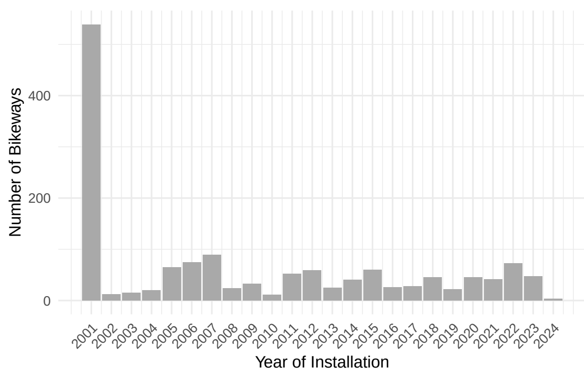
Finally, the fourth cleaning process involved classifying cycling lanes based on the type of infrastructure. Data from the 'INFRA_HIGHORDER' and 'INFRA_LOWORDER' columns was cleaned, and missing values were removed. The lanes were classified into three comfort levels: High Comfort, Moderate Comfort, and Low Comfort, depending on whether the infrastructure was protected or involved bike lanes. The classification, along with year data for installation and upgrades, was saved for analysis on the types of cycling lanes and their comfort levels. Table 5 shows how it looks like.

Table 5: Classification of Cycling Lanes by Comfort Level

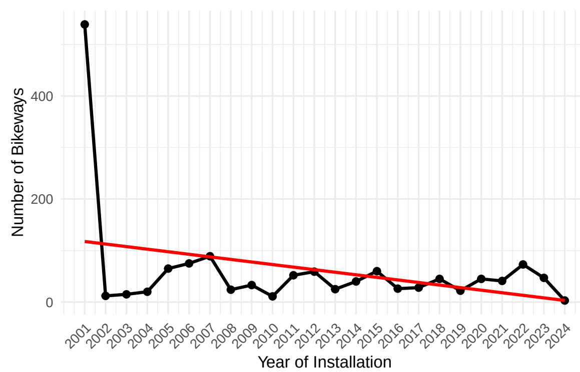
Installed Year	Upgraded Year	Comfort Level
2001	2021	Low Comfort
2001	2009	High Comfort
2001	2011	High Comfort
2001	2011	High Comfort
2001	2012	High Comfort
2001	2012	High Comfort

3 Results

3.1 Data Trend



(a) Number

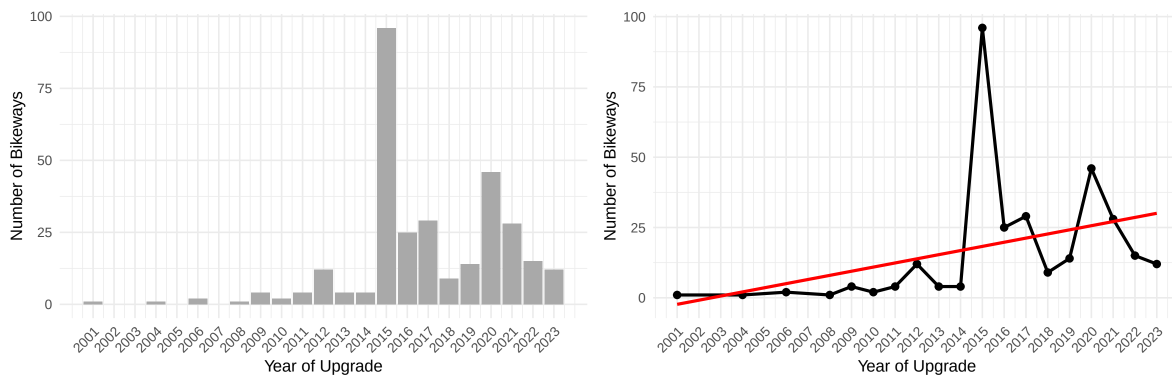


(b) Trend

Figure 1: Toronto Bikeways Installed by Year

Figure 1 consists of two panels depicting the number of bikeways installed in Toronto by year, alongside a trend analysis of the installation pattern over time. Figure 1a displays the raw count of bikeways installed per year from 2001 to 2024. A significant spike is observed in 2001, with over 400 bikeways installed in that year alone. This likely reflects a major investment in cycling infrastructure at the time. Following 2001, the number of installations drops sharply and stabilizes at much lower levels in subsequent years, with occasional small peaks around 2007, 2011, and 2021.

Figure 1b adds a trend line to the same data, showing a gradual decline in the number of bikeways installed over time. The trend line, sloping downward, indicates that despite some fluctuations, the overall pattern is a decrease in annual bikeway installations. The early 2000s marked a high point for cycling infrastructure development, but after this surge, the rate of installation has steadily declined. This trend might reflect a shift in city planning priorities or the saturation of available spaces for bikeways in certain areas. The analysis highlights the need for renewed focus on expanding cycling infrastructure to sustain or increase the momentum of bike-friendly urban development.



(a) Number

(b) Trend

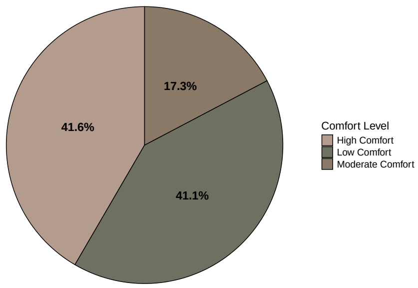
Figure 2: Toronto Bikeways Upgraded by Year

Figure 2 illustrates the number of bikeways upgraded in Toronto from 2001 to 2023, with panel (a) showing the raw counts of upgrades and panel (b) visualizing the trend. Figure 2a reveals that the most significant number of upgrades occurred in 2015, where nearly 100 bikeways were updated, marking a major peak. Outside of this spike, the number of annual upgrades remains relatively modest, typically fluctuating between 10 and 50 bikeways. Notable periods of increased upgrades are visible around 2012 and 2020, possibly reflecting concentrated efforts to modernize or expand existing cycling infrastructure in those years.

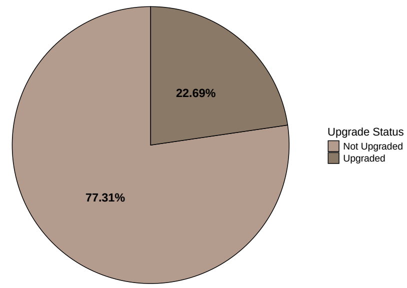
In Figure 2b, the overall trend is slightly upward, as indicated by the red trend line. Despite the notable peaks and valleys, the trend line suggests that, on average, the number of bikeway upgrades has increased over the years. The spike in 2015 significantly affects the trend, but even excluding that, the gradual rise suggests that more consistent efforts have been made to maintain and improve Toronto's cycling network. This trend aligns with broader urban planning strategies focused on making cities more accessible and environmentally friendly by supporting active transportation. The dips in recent years, particularly after 2020, might be influenced by resource reallocation or external factors, such as the global pandemic, which could have delayed infrastructure projects.

3.2 Distributions

Figure 3 provides a breakdown of Toronto's bikeway network by comfort level and upgrade status. Figure 3a shows the distribution of all bikeways based on comfort level, with the majority of bikeways classified as either Low Comfort (41.6%) or Moderate Comfort (41.1%), while High Comfort lanes constitute a smaller portion (17.3%). This indicates that while



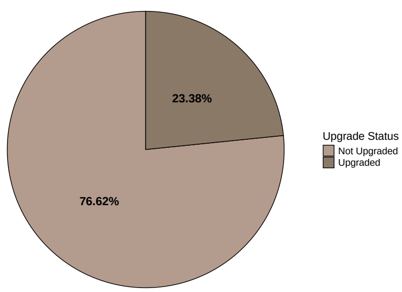
(a) Comfort Levels



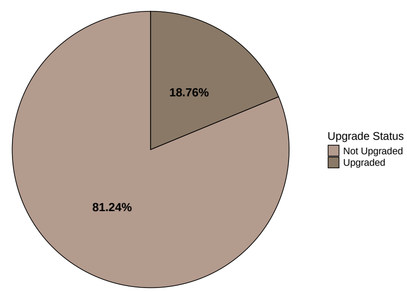
(b) Low Comfort

Figure 3: Toronto Bikeway Comfort Level Distribution

Toronto has invested in a significant number of bike lanes, most of them fall within lower comfort categories, suggesting that further improvements, particularly in upgrading existing lanes, are needed to promote safer and more comfortable cycling experiences.



(a) Moderate Comfort



(b) High Comfort

Figure 4: Toronto Bikeway Comfort Level Distribution

Figure 3b, Figure 4a, and Figure 4b offer a deeper look into the upgrade status for each comfort level. For Low Comfort lanes, only 22.69% have been upgraded, while 77.31% remain in their original state. Similarly, for Moderate Comfort bikeways, 23.38% have been upgraded, leaving 76.62% untouched. Interestingly, High Comfort lanes have the lowest proportion of upgrades, with only 18.76% improved, despite representing the most comfortable and potentially most desirable biking infrastructure. These trends highlight a potential gap in Toronto's focus on maintaining and upgrading its most comfortable and accessible cycling lanes, suggesting a need for more targeted investments in high-comfort bikeways to encourage broader use of cycling for transportation.

3.3 Maps

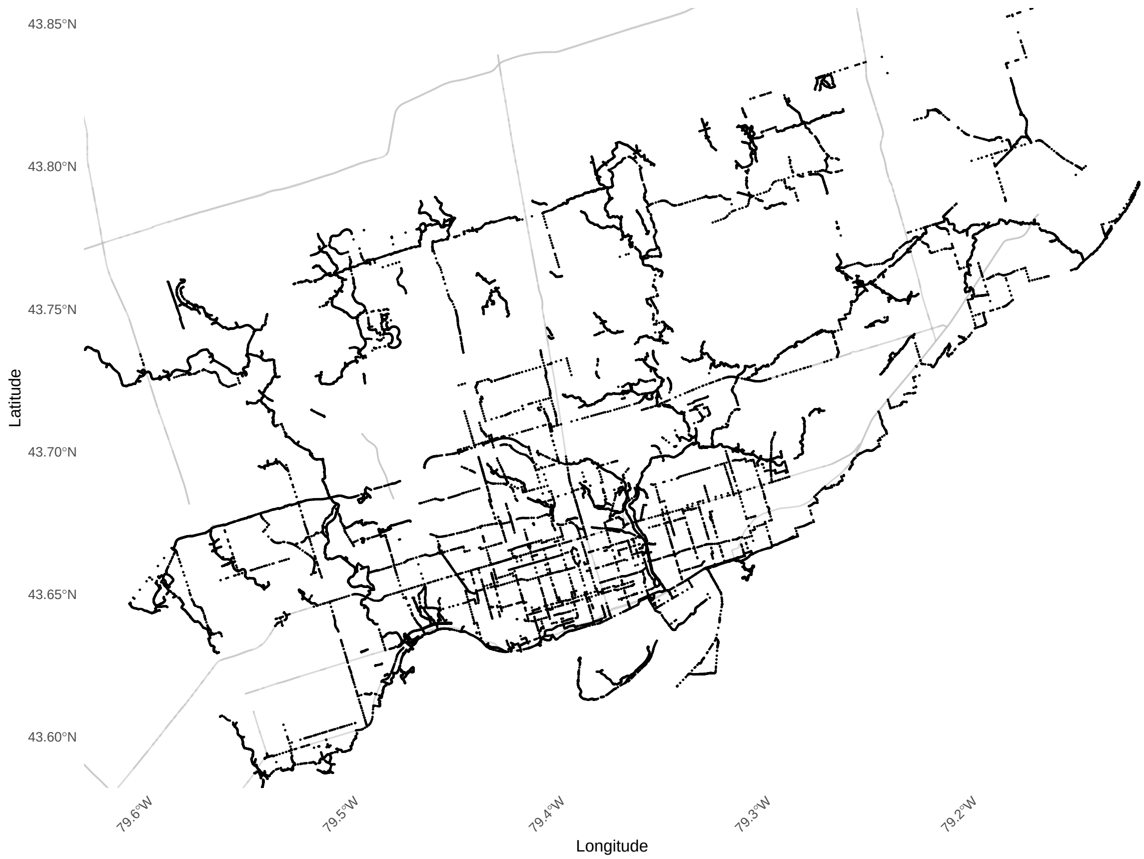


Figure 5: Map of Bike Lanes Locations in Toronto

Figure 5 provides a visual representation of the bike lane infrastructure across Toronto. The lines on the map correspond to various cycling paths, including dedicated bike lanes, multi-use paths, and shared roadways, which span different areas of the city. The geographic coordinates, ranging from around 43.60°N to 43.85°N in latitude and -79.6°W to -79.3°W in longitude, encompass most of Toronto's urban region. This map offers an important spatial perspective, illustrating the extensive network of cycling routes that connect different neighborhoods and areas within the city.

A key observation from the map is the dense concentration of bike lanes in the downtown core and along major roadways, indicating a well-established network in central Toronto. The downtown area's grid-like structure is particularly evident, showcasing a high density of lanes that facilitate easy cycling access within the city's busiest areas. As one moves further away from the city center, the map shows fewer bike lanes, suggesting that suburban regions may have less developed cycling infrastructure. However, there are notable multi-use paths extending toward the outskirts, particularly in parks and recreational areas, providing important cycling connections for those commuting or using bikes for recreational purposes.

This map highlights the importance of cycling infrastructure in promoting sustainable urban transportation. The wide distribution of bike lanes supports Toronto's efforts to enhance active transportation options, reduce traffic congestion, and improve accessibility for cyclists. The representation also provides a foundation for analyzing areas where future infrastructure developments could be prioritized, particularly in regions where cycling connectivity appears sparse.

4 Discussion

4.1 First discussion point

The results highlight Toronto's phased approach to developing its cycling infrastructure, with a significant spike in installations in the early 2000s, as shown in Figure 1. This surge is likely because the dataset started recording from 2001, hence all installations before was counted towards 2001. Futher, the fact that goverment start taking this record and the large number of installations at this period may have reflected political will and public demand for greener transportation alternatives, driven by growing concerns about climate change and urban congestion.

However, after the initial surge, the number of bikeways installed annually began to decline, a pattern that persists to this day. Several factors could explain this decline. First, the initial phase of the bike plan likely focused on areas where cycling infrastructure could be installed with relative ease, particularly in downtown Toronto, where road networks and urban density supported such investments. As the network expanded into more complex areas, such as suburban neighborhoods with fewer existing roadways, the pace of installation slowed. Additionally, the physical limitations of available space in a highly developed urban area may have constrained further expansion, as new bikeways would require more complicated and costly measures, such as road reallocation or shared-use paths.

Despite this slowdown in new installations, Figure 2 demonstrates a significant focus on upgrading existing infrastructure, particularly in later years. This shift from installation to upgrades could indicate a strategic pivot by the city toward improving the quality and safety of existing cycling infrastructure. As infrastructure ages and new safety standards emerge, upgrading older lanes becomes crucial to ensuring the network remains usable and safe for cyclists. The peak of upgrades in 2015, for example, might reflect the city's response to increased cycling activity, demands from advocacy groups, or the implementation of updated cycling policies that prioritize safer and more modern designs, such as protected bike lanes.

This pattern of prioritizing upgrades over new installations also suggests that Toronto's initial expansion may have left some areas with suboptimal or unsafe infrastructure, particularly in the form of shared roadways or painted bike lanes that offer minimal protection to cyclists. As urban transportation planning evolves, the focus has shifted toward creating more separated and protected lanes, which are essential for encouraging cycling among less experienced riders, families, or those concerned about safety. This ongoing commitment to improving the infrastructure—rather than merely expanding it—reflects a maturation in Toronto's approach to active transportation, as planners recognize that quality and safety are just as important as quantity when promoting cycling as a viable mode of transport.

Finally, another crucial aspect linked to the decline in installations could be budgetary constraints or competing infrastructure projects. As urban budgets are stretched across various priorities—public transit expansion, road maintenance, and green space development—the pace of installing new cycling lanes might slow. However, the investment in upgrades suggests that cycling infrastructure remains a priority, even if the focus has shifted from expansion to refinement. Continuing to monitor and analyze these trends will be essential for understanding how Toronto can balance its need for both new installations and the improvement of existing cycling routes to meet its long-term sustainability and mobility objectives.

In conclusion, the first discussion point highlights the evolution of Toronto's cycling infrastructure from an initial phase of rapid expansion to a more recent focus on upgrading and enhancing the safety and quality of the network. This shift reflects the challenges of balancing growth with maintenance, the need to adapt to changing urban landscapes, and the influence of global best practices and local advocacy in shaping the city's cycling future.

4.2 Second discussion point

The comfort level classification of Toronto's cycling infrastructure offers valuable insights into the quality of the city's bike network, particularly with respect to cyclist safety and usability. As shown in Figure 3, the majority of bikeways fall into the Low or High Comfort categories, with Moderate Comfort lanes—typically those offering relatively protected infrastructure—making up a smaller proportion of the overall network. This distribution suggests that, Toronto has successfully expanded the sheer number of bikeways, the majority could offer the protection and comfort necessary to encourage broader and more consistent usage. However, it is better to see Low Comfort level lanes taking the smallest portion among all.

The classification of cycling lanes into different comfort levels is important because it directly affects who feels confident enough to cycle. Low Comfort lanes, often painted bike lanes or shared roadways, offer minimal physical separation from motor vehicles, making them less appealing to risk-averse cyclists. The lack of protection increases the perceived danger, discouraging people from cycling regularly, particularly in areas with high traffic volumes. For example, a cyclist may feel comfortable using a Low Comfort lane in a quiet residential neighborhood but avoid it entirely on a busy downtown street where traffic and intersections pose greater hazards.

Moderate Comfort lanes, which typically include designated bike lanes, offer more safety but still lack the physical separation provided by protected or High Comfort infrastructure. These lanes are a step in the right direction but may not sufficiently address concerns about safety, particularly in areas with fast-moving or congested vehicle traffic. Moderate Comfort lanes are likely to attract more cyclists than Low Comfort lanes, but they may not be enough to significantly increase ridership across all demographic groups. For instance, studies have shown that women, children, and older adults are particularly sensitive to perceived danger in cycling, and without sufficient protection, these groups are less likely to use the infrastructure regularly.

High Comfort lanes, on the other hand, provide the greatest potential for encouraging cycling across a broad range of demographics. These lanes, often in the form of protected bike lanes or multi-use paths, offer a physically separated space for cyclists, reducing the likelihood of accidents involving motor vehicles. Research from cities that have invested heavily in High Comfort infrastructure, such as Amsterdam or Copenhagen, indicates that the availability of such protected lanes is a key factor in increasing overall cycling rates and making cycling a more viable and appealing transportation option for all. In Toronto, however, as the analysis shows, only a small proportion of the network is classified as High Comfort. This limits the extent to which the city can fully leverage its cycling infrastructure to promote widespread, sustained usage.

The low proportion of High Comfort lanes can be partly attributed to the early phases of Toronto's cycling infrastructure development, during which the focus was likely on quickly installing a large number of lanes to meet political and public demands. At that time, lower-cost solutions like painted bike lanes and sharrows (shared roadways) were easier and faster to implement than more expensive, space-consuming, and structurally complex protected lanes. However, these lanes did not necessarily provide the level of safety needed to support a significant increase in cycling activity, particularly among more cautious cyclists. The subsequent shift towards upgrading infrastructure, as discussed earlier, is likely an acknowledgment of the limitations of the initial approach, where quantity may have been prioritized over quality.

Moreover, the analysis reveals that many of Toronto's Moderate and Low Comfort lanes have yet to be upgraded, as shown in Figure 3b and Figure 4. For both Low and Moderate Comfort lanes, over 75% have not been upgraded, which implies that much of the city's existing cycling network still operates under outdated or less protective standards. This points to a significant gap between the current state of Toronto's cycling infrastructure and the standards that are increasingly being recognized as necessary to make cycling a mainstream mode of transportation in urban environments. The failure to upgrade a larger portion of these lanes may stem from budgetary constraints, political will, or challenges in reallocating road space in already congested or car-dominated areas.

One of the most critical implications of these findings is that Toronto's cycling infrastructure might not yet be sufficiently robust to meet the city's broader goals of reducing car dependency, lowering emissions, and promoting healthier, more active lifestyles. To truly shift a significant portion of the population towards cycling, the city will need to invest more heavily in upgrading its infrastructure, particularly in transitioning more of its Low and Moderate Comfort lanes into High Comfort lanes. This is especially important in areas where traffic volume and speed are higher, as these conditions pose greater risks to cyclists and deter people from choosing bikes as a mode of transportation.

Another potential reason for the focus on Moderate and Low Comfort lanes is the spatial distribution of the city's bikeways. As mentioned earlier when showing the result of (**fog-map?**), much of Toronto's cycling network is concentrated in the downtown core, where road space is at a premium. Installing protected lanes in these areas often requires taking road space away from cars, which can be politically and technically challenging. In contrast, suburban areas, where road space is more abundant, could offer better opportunities for the city to build High Comfort infrastructure. Expanding the reach of the cycling network into these suburban areas, while upgrading the comfort levels of existing downtown lanes, could have a transformative effect on overall cycling rates and help make cycling a viable option for longer commutes.

In conclusion, while Toronto has made considerable progress in expanding its cycling infrastructure, the comfort level analysis reveals that much of the network remains suboptimal for ensuring safety and encouraging more widespread use. To achieve its sustainability and transportation goals, the city must focus on upgrading its existing Low and Moderate Comfort lanes and prioritize the construction of High Comfort infrastructure. This shift will be crucial not only for improving safety but also for making cycling an attractive option for a more diverse range of residents, thereby promoting equity and inclusivity in urban transportation.

4.3 Third discussion point

The geospatial analysis of Toronto's cycling infrastructure, as visualized in Figure 5, reveals clear spatial patterns that highlight both the strengths and weaknesses of the city's current bike network. One of the key findings is the dense concentration of bikeways in the downtown core, where cycling infrastructure is most integrated into the existing urban fabric. This concentration aligns with expectations, as downtown Toronto is the city's most densely populated and heavily trafficked area, where the demand for alternative transportation modes is highest. The high density of bikeways in the city center reflects a concerted effort to provide accessible cycling options in areas where they are most likely to be used, particularly by commuters and urban residents.

However, the map also exposes a noticeable gap in cycling infrastructure as one moves further from the city center. The relative sparsity of bike lanes in suburban and peripheral areas suggests that while downtown residents enjoy a well-connected cycling network, those living in the suburbs have fewer options for safe, comfortable bike routes. This discrepancy may limit the overall effectiveness of Toronto's cycling infrastructure, as it primarily serves those in the urban core while potentially neglecting a significant portion of the population. Suburban residents, who often have longer commutes and fewer public transit options, could benefit greatly from expanded cycling infrastructure that offers a viable alternative to car travel.

The lack of infrastructure in suburban areas could be attributed to a variety of factors. Suburbs typically have lower population densities and wider roads, making cycling infrastructure less of a priority in urban planning compared to the densely populated downtown core. Additionally, suburban regions tend to have more car-dependent cultures, where cycling is not as ingrained as a common mode of transportation. The existing infrastructure may therefore reflect historical priorities that favored cars over active transportation. However, as cities like Toronto strive to reduce traffic congestion and meet climate goals, expanding cycling infrastructure into these suburban areas could be a crucial step toward encouraging more sustainable transportation choices.

Furthermore, the map shows the importance of major recreational areas, such as parks and waterfronts, in Toronto's cycling network. Multi-use trails, which provide High Comfort lanes, are particularly prevalent in these areas, offering scenic and safe routes for cyclists. While these trails are beneficial for recreational cycling, they may not be fully integrated into the city's transportation network, limiting their utility for commuters. Connecting these trails to the downtown core and other major employment hubs could improve their role in promoting cycling as a legitimate form of daily transportation rather than just a leisure activity.

Lastly, the map highlights potential future opportunities for infrastructure expansion. Areas with sparse cycling routes could be prioritized for new installations, especially where there is existing road capacity or public demand for safer cycling options. Identifying and addressing these gaps will be crucial as Toronto continues to grow and seeks to make its transportation system more equitable and sustainable. The current infrastructure is heavily concentrated in downtown areas, but future developments could focus on creating a more geographically balanced network, ensuring that all residents, regardless of location, have access to safe and convenient cycling routes.

In summary, the geospatial distribution of Toronto's cycling infrastructure reveals a well-connected downtown network but highlights the need for more investment in suburban areas and better integration of recreational trails into the broader transportation system. Expanding the reach of cycling infrastructure into underdeveloped areas will be key to making cycling a viable transportation option for a larger portion of the city's population.

4.4 Weaknesses and next steps

One key limitation of this study is the reliance on the 'Cycling Network' dataset from OpenDataToronto, which, while comprehensive, might not capture informal or emerging cycling routes that are not officially recognized. Additionally, the dataset may not include newer infrastructure developments if updates were delayed in publication. Future research should integrate real-time data collection techniques or alternative datasets (e.g., crowdsourced information) to ensure that the analysis reflects the most current state of the network.

Another weakness lies in the classification of comfort levels, which, while useful, is a simplification. Comfort in cycling can be influenced by numerous factors beyond infrastructure type, such as traffic density, road conditions, and seasonal weather. A more nuanced classification that incorporates these additional factors could provide a more accurate assessment of how comfortable Toronto's cycling network truly is for different types of cyclists.

Next steps should include focusing on identifying areas with fewer bike lanes and lower comfort levels, particularly in suburban areas. These regions could be targeted for infrastructure upgrades and expansion to promote greater equity in access to safe cycling options. Additionally, analyzing cycling usage patterns, perhaps through mobile GPS data or surveys, would offer valuable insights into how the infrastructure is being utilized, helping city planners to make data-driven decisions in future expansions or upgrades.

A Appendix

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