

1 A comparison of objective attributes and cyclists' perceptions along cycling
2 routes in a Canadian developing cycling city

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7 **Abstract**

8 **Background:** Cycling is known to have many health benefits. For this reason, transport planners and public
9 health officials in Canada increasingly aim to encourage cycling for transport. On- and off-street infrastructure is
10 often implemented to facilitate cycling and planners rely on a range of tools for informing the design of the
11 network of facilities. This mixed methods study compares objectively measured attributes and cyclists'
12 perceptions of the built environment along inferred cycling routes in Hamilton, Ontario.

13 **Methods:** Environmental audits were conducted along six cycling routes in Hamilton to document the attributes
14 that might support or hinder cycling. The routes were inferred based on the output of a model of cycling flows.
15 Cyclists, 9 male and 5 female, then participated in semi-structured interviews where they reviewed photos of the
16 routes and described their perceptions and preferences. Interview data were analyzed using both inductive and
17 deductive thematic analysis based on the categories of the audit instrument.

18 **Results:** Cyclists prefer routes that have dedicated cycling infrastructure, or residential streets with low volumes
19 of traffic even if they lack infrastructure. They dislike routes with busy arterial roads or that lack cycling
20 infrastructure. Their experience and knowledge of cycling in a city transitioning to be more bicycle-friendly
21 revealed preferences that can help to improve existing infrastructure and cycling routes, which may also help to
22 reduce barriers for non-cyclists.

23 **Conclusions:** The use of photos is an innovative and practical approach to explore perceptions of regular
24 cyclists, which can be leveraged to inform policies and interventions to make cycling routes and infrastructure
25 safer and more attractive. Transport planners in developing cycling cities should pay attention to a broad range
26 of built environment factors that influence where people choose to cycle.

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27 **1. Introduction**

28 Many Canadian cities have adopted pro-cycling policies and programs in recent years to support the uptake of
29 cycling for transport, including a range of interventions from investments in infrastructure to educational
30 programs or promotional events (Assunçao-Denis and Tomalty, 2019). Large population health gains
31 (Celis-Morales et al., 2017) and improved environmental conditions in urban areas (Zahabi et al., 2016) could be
32 achieved if cycling became more mainstream. For instance, Raustrop and Koglin (2019) estimated that if nearly
33 half of the residents in Scania county, Sweden cycled to work, almost 20 percent would meet physical activity
34 guidelines from utilitarian travel alone. The challenge, however, is how to successfully transition from commonly
35 car-centric North American cities, to bicycle-friendly cities with larger shares of active travel.

36 Eudaimonic values such as freedom, enjoyment, and happiness, are often associated with active travel, even by
37 users of other modes (Mella Lira and Paez, 2021). However, to be able to convince travelers to adopt active
38 modes it is also necessary to create social and built environments that are bicycle-friendly. Short distances are
39 ideal for cycle trips, which makes compact mixed-used areas attractive for cycling (Handy, 2020; Pucher and
40 Buehler, 2008). Streets with slow traffic and traffic calming devices can also encourage people to use the bicycle
41 for transport (Mertens et al., 2017). Other features such as adequate lighting and greenery have been found to
42 support or motivate cycling (Winters et al., 2011), in addition to increased address and street density (Gao et al.,
43 2018). Furthermore, cycling experts from both The Netherlands and New Zealand agree that cycling
44 infrastructure is a universal prerequisite in countries with an established culture of cycling for transport and in
45 countries with low levels of cycling (Adam et al., 2020).

46 Likely for this reason, cities where cycling is less mainstream have started building infrastructure to encourage
47 more cycling.

48 The case of Seville, Spain is a great example of the success that can be achieved by implementing a network of
49 connected facilities at a rapid pace (Marqués et al., 2015). Revealed and stated preference studies have been
50 further informative about the types of environments that cyclists prefer and have reinforced that cycling
51 infrastructure is fundamentally important. Using global positioning system (GPS) data, several studies have
52 found that cyclists travel routes that have on-street and off-path cycling facilities and streets with low volumes of
53 traffic (???: Broach et al., 2012; Dill, 2009; Lu et al., 2018; Misra and Watkins, 2018). Stated preference studies
54 also indicate that cyclists dislike mixing with traffic and prefer dedicated infrastructure (*inter alia*, see Clark et
55 al., 2019; Caulfield et al., 2012; Stinson and Bhat, 2003; Veillette et al., 2019; Winters et al., 2011).

56 Cities with low but growing levels of cycling have been called “developing cycling cities” (Liu et al., 2020), “low
57 cycling maturity” cities (Félix et al., 2019), “emerging cycling cultures” (Clark et al., 2019), or “starter cycling
58 cities” (Meireles and Ribeiro, 2020). People who currently cycle in these settings are in the unique position of
59 observing and experiencing how the city changes over time to become more bicycle-friendly. Their experiences
60 can highlight the extent to which a city’s current efforts support or hinder cycling. A few studies in developing

61 cycling cities have found a similarity in route preferences and barriers to cycling between cyclists and non-cyclists
62 (see Félix et al., 2019; Clark et al., 2019; Winters and Teschke, 2010) which also suggests that the perspectives of
63 regular cyclists may also be informative about what could be improved to encourage more people to cycle.
64 A variety of qualitative methods that examine the experience and perceptions of cycling in such settings can
65 help to centre the cycling experience in route and infrastructure design. For example, interviews or mapping
66 exercises (see Manton et al., 2016; Marquart et al., 2020) and ride-alongs (van Duppen and Spierings, 2013) may
67 shed more light on reasons for where people cycle and how cycling is experienced. Other methods that hold
68 promise for cycling research are photovoice and photo elicitation, techniques that have been used to explore
69 the link between transportation and well-being (Guell and Ogilvie, 2015; Ward et al., 2015) and perceptions
70 of the built environment (???: ???). These approaches involve the use of images or photographs in qualitative
71 interviews to evoke memories, feelings, and experiences about a research phenomenon (Harper, 2002). Photo
72 elicitation is well-suited for prompting discussion and developing a comprehensive description of cycling issues,
73 and builds upon the use of photos in stated preference surveys (see Clark et al., 2019) by enabling participants
74 to recall and share perceptions or experiences that influence travel preferences. Environmental audits can also be
75 a useful tool to document how the built environment supports active travel (Moudon and Lee, 2003), and have
76 been used in studies to explore walkability. Qualitative evidence captured from photo elicitation or interviews can
77 thus complement objective assessments of the physical environment studied through methods like environmental
78 audits or GIS (see Lee and Dean, 2018), and has the potential to inform mobile applications or platforms to
79 induce cycling (see Meireles and Ribeiro, 2020).

80 In this paper, a sequential explanatory mixed methods approach compares objectively measured attributes and
81 cyclists' perceptions of the built environment along inferred cycling routes in Hamilton, Ontario. This project
82 explored the influence of the built environment on cycling in a mid-sized Canadian city with low but growing
83 cycling levels. We previously estimated a spatial interaction model to investigate the correlates of cycling in
84 Hamilton and found that the *quietest* distance route between cycling trip zones of origin and destination inferred
85 by *CycleStreets* best explained cyclist travel in Hamilton and led to the most parsimonious model [paper
86 submitted to *Transportation*]. Given that the routes were inferred, we did not know the quality of their built
87 environment or how well they match where cyclists actually travel in Hamilton. To further explore these
88 objectives, we audited 6 inferred routes to document attributes that might influence cycling. We then used
89 photos of the routes, or photo-journeys, in 14 semi-structured interviews with regular cyclists to examine their
90 perceptions of the routes.

91 **2. Methods, Research Setting, and Materials**

92 *2.1. Research Setting*

93 Hamilton is a mid-sized city located in Canada with a population of roughly 740,000 according to the 2016
94 Canadian Census (Statistics Canada, 2017). The city is relatively flat but is separated by the Niagara
95 Escarpment, referred to locally as “the mountain”, which can be as high as 100m in many places. The rural and
96 suburban parts of the city are on top of the Escarpment and the lower city and downtown core are below [see
97 Figure 1 for reference]. Similar to other Canadian cities, cycling levels have grown in recent years; the mode share
98 of cycling for transport doubled from 0.6% in 2011 to 1.2% according to the 2016 *Transportation Tomorrow*
99 *Survey (TTS)* (Data Management Group, 2018). This voluntary travel survey is conducted every 5 years to
100 collect information about urban travel for commuting purposes in Southern Ontario (Data Management Group,
101 2018). Between the 2011 and 2016 surveys, the City of Hamilton implemented a public bicycle share program
102 (PBSP) and added 85 kilometres of bicycle lanes. Hamilton is the only mid-sized city in Canada with a PBSP
103 which reflects that the City has invested a lot of effort in the potential for Hamilton to become a mid-sized
104 cycling city in North America. As of 2019, approximately 46% of the cycling network has been built and
105 approximately 15 to 20 km of new facilities are added each year. The City’s current Cycling Master Plan states
106 that the goal is to implement all proposed infrastructure by 2029 (City of Hamilton, 2018a), but the City’s
107 typical annual investment in cycling infrastructure falls short of what is needed to meet this goal. Therefore, it is
108 suggested that Hamilton is a developing cycling city because it is currently in a state of transition and has
109 growing cycling levels. The City is at the mid-way point in the development of its cycle infrastructure network.
110 Other interventions have been implemented to increase cycling levels, but the cycling culture is still growing and
111 the network is currently fragmented.

112 This paper contributes to the growing body of research on cycling and active travel in mid-sized Canadian cities
113 in recent years (Fischer et al., 2020; Klicnik and Dogra, 2019; Mayers and Glover, 2020; Winters et al., 2018).
114 Mid-sized cities in Ontario offer unique opportunities for future growth and development despite but face existing
115 challenges to transportation and land use planning (Evergreen, 2017). In the case of Hamilton, efforts to increase
116 pedestrian and cyclist-friendly spaces are constrained by the city’s efforts in the mid-1900s to prioritize
117 automobile traffic on arterial roads (Leanage and Filion, 2017). Despite the legacy of Hamilton’s car-oriented
118 streets, building a cycling network in mid-sized cities is promising because of short trip distances (Winters et al.,
119 2018), which can make cycling appealing given the proper investment in supportive infrastructure. Indeed,
120 further analysis of the 2016 *TTS* revealed that 35% of all current trips in Hamilton are 5 km or less (Mitra et al.,
121 2016), which means that these trips could be cycled. The City of Hamilton also aims to have 15% of the mode
122 share be comprised of walking and cycling trips by 2031 (City of Hamilton, 2018b). In this stage of transition,
123 there is the potential to incentivize modal shifts that specifically increase opportunities for physical activity.

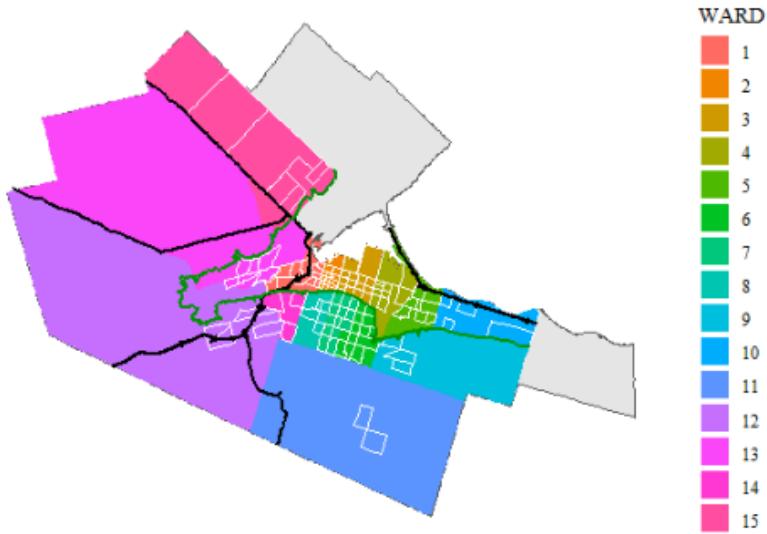


Figure 1: The number of cycle trips reported for each traffic analysis zones in the city of Hamilton that produced cycle trips. The number of cycle trips (ranging from more than 1 to over 1097) are shown by the colour gradient. Most cycle trips reported occur around the University.

124 *2.2. Previous Research*

125 In the first phase of this project, [paper submitted to *Transportation*], we used bicycle trip data from the 2016
 126 TTS to develop a spatial interaction model that investigated the built environment correlates of cycling flows in
 127 Hamilton. While the *TTS* is informative about the traffic zones of origin and destination of cycling trips, it does
 128 not reveal the route choice of respondents. Thanks to the growth in open source resources for transportation
 129 analysis (Lovelace, 2021), a novel feature of this model was the use of a cycle routing algorithm to infer different
 130 types of cycle routes between zones of origins and destinations (Lovelace and Lucas-Smith, 2018). The centroid of
 131 each traffic analysis zone, the geographical unit of analysis used by the *TTS*, serves as the start and end point for
 132 these inferred routes. The distance and time of three different types of routes, characterized as *fastest*, *quietest*, or
 133 *balanced* by the *CycleStreets* algorithm, were used as measures of impedance in the model. Briefly, the R package
 134 states, “These represent routes taken to minimize time, avoid traffic, and compromise between the two,
 135 respectively” (Lovelace and Lucas-Smith, 2018, p. 1). Additional details about the algorithm are available online.
 136 The model revealed that inferred *quietest* routes that allow cyclists to minimize distance and interactions with
 137 other road users best explain the pattern of travel by bicycle in Hamilton [paper submitted to *Transportation*].
 138 The *quietness* score takes into account attributes of the road, mainly the presence or absence of cycle
 139 infrastructure. Our findings suggests that cyclists in Hamilton are seeking out routes that enable them to avoid
 140 traffic while potentially maximizing the use of residential streets over arterial roads. We then used the model to
 141 identify trip flows where there was more or less cycling than expected (i.e., reported number vs. predicted number
 142 of cycle trips). The model did not capture any route-level characteristics beyond the data available for Hamilton
 143 through *OpenStreetMap* that was used by the algorithm. Therefore (see Moniruzzaman and Páez, 2012), it was
 144 hypothesized that more cycling occurred between zones of origin and destination that were under-estimated

145 because the inferred routes facilitate cycling (meaning that there was *more* cycling between the zones than
146 predicted by the model), for example through the provision of infrastructure. Conversely, cycling trips may have
147 been over-estimated if routes between zones of origin and destination are less supportive of cycling (meaning that
148 there was *less* cycling between zones than predicted by the model).

149 *2.3. Methods*

150 *2.3.1. Environmental Audits*

151 We conducted environmental audits along 6 inferred routes that were most substantially over- or under-estimated
152 by the model. The *Systematic Pedestrian and Cycling Environmental Scan (SPACES)*¹ (Pikora et al., 2002) was
153 selected because it documents the presence or absence of observable characteristics that are potential influences of
154 walking and cycling. The framework describes four domains of the built environment that influence physical
155 activity: functional, safety, aesthetic, and destination (Pikora et al., 2003). The instrument was developed for use
156 along street segments within neighbourhoods around a residential location. While the cycling trip flows in
157 Hamilton occur beyond the 400 m neighbourhood range, our unit of analysis, namely segments of a street, is the
158 same as the *SPACES Instrument*. The instrument also includes an extensive range of measurable features that
159 have been identified in the literature which meet our objective in conducting an exploratory and descriptive
160 analysis of attributes along the inferred cycling routes. For these reasons, we determined that the *SPACES*
161 *Instrument* was suitable for our purposes. This instrument was also selected because it is relatively simple to use
162 and developed for research purposes (Moudon and Lee, 2003). The instrument comes from the field of health and
163 the factors included in the audit were guided by stakeholder interviews and a Delphi study (Pikora et al., 2003).
164 The *SPACES Instrument* was adapted to the local context in Hamilton. Cycling was the primary focus of this
165 study; accordingly, some factors that were less influential on cycling, according to the literature, were removed for
166 ease of data collection. The features that were removed from the instrument used in this study include:
167 *permanent path obstructions, pedestrian crossing aids, surveillance, building design, and driveway crossovers.*
168 Other features were combined: all types of maintenance instead of specific categories, and the types of paths. A
169 broader range of cycling facilities, buildings, and traffic calming measures that are found in Hamilton were also
170 added. The modified *SPACES Instrument* is shown in Appendix A and the Hamilton cycling guide added to the
171 *SPACES Observation Manual* is found in Appendix B. The first author and three research assistants conducted
172 the audits during October and November 2019. The first author was the only auditor who has cycling experience
173 in Hamilton. Each auditor participated in a training exercise led by the first author to become familiar with the
174 *SPACES Instrument* and the *SPACES Observation Manual*² (Pikora et al., 2002), and to standardize the way in
175 which the audits were carried out. The majority of routes ($n = 4/6$) were audited by a pair of research assistants

¹SPACES Audit Instrument

²SPACES Observation Manual

Table 1: Demographics of participants (age, gender, self-reported frequency of cycling, and self-reported confidence level).

Participant	Age	Gender	Frequency	Confidence
1	18-24	Male	Every day	Excellent
2	25-44	Male	Multiple times a week	Excellent
3	25-44	Female	Multiple times a week	Excellent
4	25-44	Male	Multiple times a week	Excellent
5	45-64	Male	Multiple times a week	Good
6	45-64	Male	Every day	Excellent
7	45-64	Male	Multiple times a week	Excellent
8	45-64	Male	Multiple times a week	Good
9	25-44	Female	Multiple times a week	Excellent
10	25-44	Male	Every day	Excellent
11	25-44	Female	Multiple times a week	Good
12	25-44	Female	Every day	Excellent
13	25-44	Male	Every day	Excellent
14	25-44	Female	Multiple times a week	Excellent

176 who filled out the instrument together. Two routes ($n = 2/6$) were audited by the first author alone. The
 177 auditors were instructed to discuss any disagreements and reach consensus before filling out the instrument. Once
 178 the audits were completed, the features of each route segment were manually recorded in an Excel sheet by the
 179 first author. Any perceived errors in data collection were reviewed using Google Street View and were corrected
 180 by the first author. A descriptive analysis of each route was performed to determine the presence and frequency
 181 of features along each route.

182 *2.3.2. Interviews*

183 **Less narrow view, not static, more temporal**

184 Following the audits, 14 cyclists in Hamilton were recruited to participate in a 90-minute semi-structured
 185 interview [see Table 1 for demographics of participants]. We employed a convenience sampling strategy to recruit
 186 participants using posters in local bike stores and coffee shops in Hamilton and a social media post on Twitter. A
 187 total of 28 people responded to the recruitment notice, and the first 14 who met the inclusion criteria were
 188 recruited to the study. Inclusion criteria were as follows: age (18 years of age or older) and regular travel by
 189 bicycle for transport in Hamilton. The latter was defined as cycling for transport at least once per week.
 190 The first author conducted the interviews, ranging in time from 60 to 90 minutes, between November 2019 and
 191 January 2020 at either the institution, a local coffee shop, or local library. Participants were presented with three
 192 packages of photos that each contained two routes (i.e., the first package contained routes 1A and 1B; the second
 193 contained routes 2A and 2B; and the third contained routes 3A and 3B). Table 2 provides a description of the
 194 routes. This approach can be considered a form of photo elicitation (Harper, 2002), whereby images are used
 195 to prompt memory, emotions, and experience of a particular phenomenon (e.g., identity, culture, place, etc.).
 196 The photos of the routes audited were taken from Google Street View, using the most recent photos available
 197 to ensure that they matched the current streetscape as much as possible. As such, the time of day or day of
 198 the week that the photos were taken may not reflect prime cycling times and likely traffic volumes expected at

199 those times. We used photos to understand how these routes were perceived or experienced based on cyclists' 200 knowledge or history of traveling through these spaces. In contrast to photo elicitation, which typically uses 201 standalone photos of a particular item of interest (e.g., infrastructure design or route type), a novel aspect of 202 our approach is the sequential nature of the photos presented in the interviews. Therefore, these photo journeys 203 include a more dynamic, temporal element that allows participants to follow the route, and see and comment on 204 the changes that they perceive. This enables us to capture both perceptions of specific attributes of the routes as 205 well as the experiences or impressions of the journey as a whole.

206 The first two packages each had one route where cycling was over-estimated by the original model (i.e., 1A and 207 2A), and one route where cycling was under-estimated by the original model (i.e., 1B and 2B). The final package 208 had two routes where cycling was under-estimated (i.e., 3A and 3B). The routes in each package were paired 209 according to their length and number of segments [see Table 2]. Participants did not know which routes were 210 over- and under-estimated. The photos for each route were numbered to make it easier to transcribe and ensure 211 that participants' comments could be attributed to the appropriate segment. Segments that were long or that 212 had changing attributes in the same segment were depicted through multiple photos. Participants were asked to 213 look through the photos of each route from start to finish and then to share their perceptions by commenting on 214 what they liked and disliked about the route. However, some participants preferred to make comments as they 215 looked through the photos. After commenting on both routes in one package, participants were asked which route 216 they preferred. Additional questions were asked if a participant reported having cycled part of a route or if they 217 described taking a different route than the one inferred. Other follow-up probing questions were asked to better 218 understand participants' perceptions or experiences of the route.

219 The interviews were audio recorded and later transcribed using Temi, an online AI-based transcription software. 220 The first author then reviewed and proofread each transcript. The first author coded all of the interviews and 221 conducted a thematic analysis using both inductive and deductive approaches (Braun and Clarke, 2006). Themes 222 were determined by the frequency of codes (Braun and Clarke, 2006), meaning the number of different 223 participants who expressed a similar like, dislike, or perception for each route. Themes identified using a 224 deductive approach aligned with the attribute categories from the *SPACES Instrument*, while other themes were 225 identified using an inductive approach based on perceptions and experiences that emerged in the interviews.

226 Themes were identified for each individual route and not for the collective of six routes.

227 2.3.3. Ethics

228 This study was approved by the institution's research ethics board in September 2019.

Table 2: Description of inferred routes that were audited using the SPACES Instrument.

Route	Origin	Destination	Distance	Number of Segments	Number of Photos
1A	Dundas	West Hamilton	2.3 km	13	19
1B	East Mountain	East Mountain	1.3 km	10	17
2A	Downtown Hamilton	West Hamilton	5.3 km	27	34
2B	East Hamilton	East Hamilton	4.7 km	31	36
3A	Stoney Creek	Stoney Creek	3.6 km	19	23
3B	Downtown Hamilton	Downtown Hamilton	2.5 km	20	25

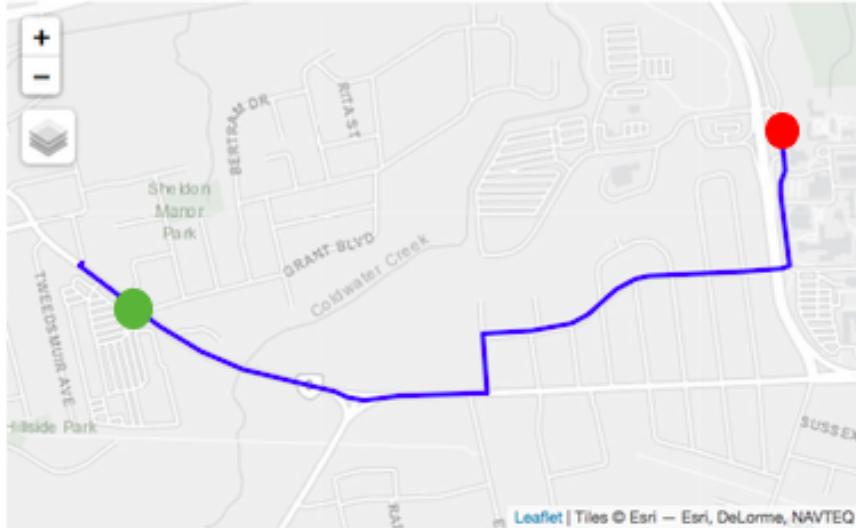


Figure 2: Map of route 1A.

229 3. Findings

230 3.1. Observable Route Attributes Measured using the SPACES Instrument

231 A total of 6 inferred routes were reviewed by 14 cyclists [see Table 2]. The results of select objective route
 232 attributes are presented in Table 3. The characteristics documented from the *SPACES Instrument* are presented
 233 only for the right side of the street where cyclists would typically travel. It is important to note that attributes
 234 are only documented in one direction along the routes. Each route is accompanied by a map of the street network
 235 from origin to destination and by one or more photos to illustrate segments with attributes that elicited
 236 comments from many participants. The full results of the audits are available in a Google Drive folder:

237 https://drive.google.com/drive/folders/1tYFPrlNgsF_LffzZferBMeMQOcUu3MIH?usp=sharing

238 3.2. Cyclists' Perceptions of the Cycling Routes

239 3.2.1. Package 3

Table 3: Results of the objectively measured attributes by percentage of segments along the inferred cycle routes.

Attribute	Route.1A	Route.1B	Route.2A	Route.2B	Route.3A	Route.3B
<i>Predominant buildings/features</i>						
<i>Transport infrastructure</i>	0	0	3.7	3	0	5
<i>Housing</i>	69	80	63	58	63	40
<i>Office</i>	0	0	0	0	0	10
<i>Food (grocery, restaurant)</i>	8	0	0	3	0	0
<i>Retail</i>	8	0	3.7	0	5	5
<i>Other retail (gas station, etc.)</i>	0	0	0	0	0	0
<i>Industrial</i>	0	0	3.7	0	21	0
<i>Educational</i>	8	0	11.1	7	0	5
<i>Service</i>	8	0	3.7	26	5	30
<i>Natural features</i>						
<i>Cycling facilities</i>	0	20	11.1	3	5	5
<i>Sharrows</i>	0	0	4	0	0	0
<i>Signed route</i>	8	80	7	55	0	10
<i>Bicycle lane - marked</i>	54	0	26	0	0	5
<i>Buffered bicycle lane</i>	0	0	4	0	0	10
<i>Protected bicycle lane</i>	0	0	0	0	0	10
<i>Two-way cycle track</i>	0	0	0	0	0	60
<i>Multi-use trail</i>	0	0	15	3	0	0
<i>Bike path</i>	0	0	0	0	0	0
<i>Paved shoulder</i>	0	0	0	0	0	0
<i>No facilities</i>	38	20	44	42	100	5
<i>Cycling facility has flat or gentle slope</i>	100	88	93	100	N/A	84
<i>Cycling facility has moderate slope</i>	0	12	7	0	N/A	11
<i>Cycling facility has steep slope</i>	0	0	0	0	N/A	5
<i>Road condition is good</i>	92	100	63	55	68	90
<i>Road condition is moderate</i>	8	0	22	29	32	10
<i>Road condition is poor</i>	0	0	0	0	0	0
<i>Road is under repair</i>	0	0	0	16	0	0
<i>1 traffic lane</i>	77	100	63	55	79	30
<i>2 or 3 traffic lanes</i>	23	0	19	42	21	70
<i>4 or 5 traffic lanes</i>	0	0	0	3	0	0
<i>6 or more lanes</i>	0	0	0	0	0	0
<i>Traffic calming devices</i>	0	0	7	0	0	0
<i>Traffic signal</i>	23	10	22	13	11	80
<i>Bike signal</i>	0	0	0	0	0	10
<i>Bike box</i>	0	0	0	0	0	15
<i>Bridge or overpass</i>	0	0	4	3	0	0
<i>Streetlights are present</i>	31	60	59	19	21	50
<i>Over 75% of street is well maintained</i>	100	100	88	81	95	100
<i>Street is clean (no litter, graffiti, etc.)</i>	100	100	100	97	84	100
<i>1 or more trees per block</i>	100	80	66	19	89	80
<i>Approx 1 tree for every 2 blocks</i>	0	0	4	20	0	0
<i>No trees at all</i>	0	20	30	61	11	20
<i>Very attractive for cycling</i>	54	10	11	3	0	20
<i>Attractive for cycling</i>	23	70	52	36	58	55
<i>Not attractive at all for cycling</i>	23	20	37	61	42	25
<i>Easy to cycle</i>	62	10	37	3	0	60
<i>Moderately difficult to cycle</i>	15	70	48	61	53	25
<i>Very difficult to cycle</i>	23	20	15	36	47	15



Figure 3: Segment 2 of route 1A depicting two or three lanes in each direction and no cycling facilities on the roadway. Lighting and natural views are present. (Source: Google Street View)

240 3.2.1.1. *Route 1A*³. Most participants reported being familiar with this route; they had previously cycled at
241 least part of the route or in this general area. The majority of participants disliked the segments with a four-
242 lane arterial road that lacked infrastructure, and more than half stated that they would not cycle this part of
243 the route. Factors that made them dislike these segments include the lack of cycling facilities, number of traffic
244 lanes, the width of the lanes, and the hilliness (see Figures 3 and 4). Most participants expected car traffic to be
245 moving faster on these segments.

246 A few participants who were familiar with the area reported that they would have cycled the Hamilton-Brantford
247 Rail Trail instead, an off-street multi-use trail parallel to the arterial road. Some cyclists noted that there was no
248 sidewalk or shoulder on the right side of the roadway where they would be cycling, with some describing that it
249 would make them feel “*uncomfortable*” or “*anxious*” without that space. In general, the arterial road without
250 infrastructure was perceived to be too busy and not designed for cycling. The left turn at an unsignalized
251 intersection was also noted as difficult by a few participants (see Figure 5).

252 However, the route was generally perceived positively once it entered a residential area. The majority of
253 participants reported liking or had positive comments of the segments that had an on-street marked bicycle lane
254 (see Figure 6). Most participants also liked these segments because they were perceived to be “*residential*” or
255 “*quiet*”, and not as busy in terms of car volume. Some participants reported liking the green space and nature
256 along the on-street marked bicycle lane. In addition, half of the participants stated that they liked the
257 pedestrian-activated traffic signal because it enabled them to cross the arterial road promptly and safely (see

³This route was slightly adjusted for the audit. Rather than starting midblock, the audit started one block south at the commercial plaza. Recall that the origin of each inferred route is the centroid of the traffic analysis zone, so this is not the true origin of this cycling flow.



Figure 4: Segment 2 of route 1A depicting the uphill section on a 2 lane arterial road with no on-street cycling infrastructure. (Source: Google Street View)



Figure 5: Segment 4 of route 1A depicting the urban design of the street when making a left turn to follow the City's signed bicycle route. (Source: Google Street View)



Figure 6: Segment 9 of route 1A depicting the on-street marked bicycle lane in a residential neighbourhood. (Source: Google Street View)



Figure 7: Segment 13 of Route 1A depicting a pedestrian-activated signal to cross a an arterial road. (Source: Google Street View)

258 Figure 7).

259 3.2.1.2. *Route 1B*. While none of the participants were familiar with this route, this route received overall
260 positive comments. Cyclists primarily liked the route because it was perceived to have low traffic, fewer cars, and
261 was quiet or residential. Some words used to describe the route include “*nice*”, “*lots of trees*”, and “*not busy*”
262 (see Figure 9). The lack of infrastructure was noted by some participants but only two reported that they disliked
263 this aspect of the route. Only one participant noticed that it was a signed route, but participants reported that
264 they would generally feel comfortable cycling this route. A few participants commented on the good quality of
265 the pavement. Although the route was perceived to be low traffic and residential, some cyclists would still have
266 preferred if the route had a dedicated cycling facility. Four participants noticed or liked the 40 kilometres/hour
267 speed limit on the route.

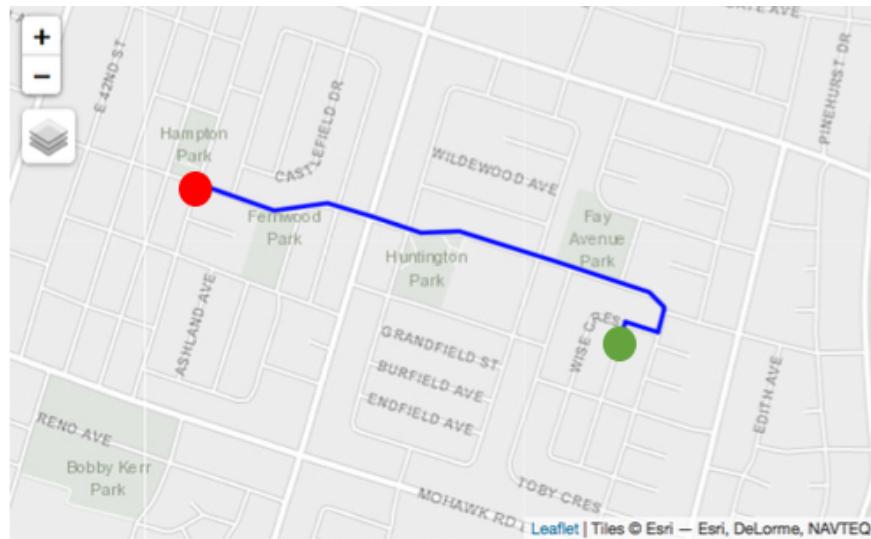


Figure 8: Map of route 1B.



Figure 9: Segment 4 of route 1B depicting the streetscape on a signed route in a residential area. (Source: Google Street View)

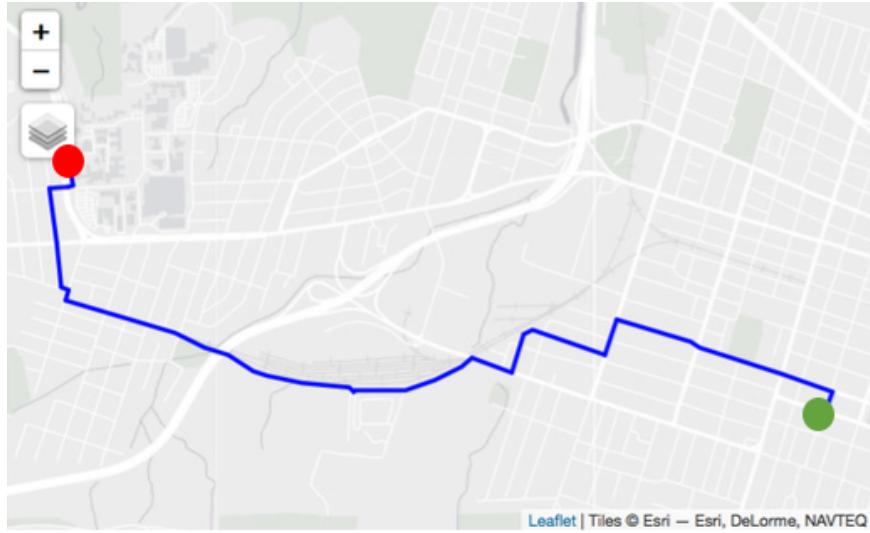


Figure 10: Map of route 2A.

268 3.2.2. Package 2

269 3.2.2.1. Route 2A⁴. Participants were familiar with this route and had previously cycled the entire route or parts
 270 of it. Cyclists reported liking the infrastructure, particularly the on-street marked bicycle and the Hamilton-
 271 Brantford Rail Trail, which is an off-street multi-use path (see Figure 11 and Figure 12). The Rail Trail was
 272 perceived to be ideal for cycling: one participant called it a “*superhighway for bicycles*”, another described it as
 273 a fundamental “*arterial route*” for cyclists in Hamilton. Most participants also liked that many sections of the
 274 route that did not have dedicated infrastructure were on residential streets. Several cyclists liked or noticed that
 275 the route connected them to or passed by key destinations.

276 There were four areas or features along the route that participants disliked or that were more poorly perceived.
 277 First, several participants disliked or expressed concern about turning left at an intersection without a signal
 278 after the bike lane ends. Cyclists who disliked this feature reported often waiting a while to turn left, that it was
 279 challenging for them that motorists did not always anticipate their need to transition lanes like other road users,
 280 or that they were not given enough space (see Figure 13).

281 Second, the short stretch along an arterial road with two traffic lanes in each direction and no dedicated cycling
 282 infrastructure (see Figure 14) was strongly disliked by most participants. Others had mixed perceptions or
 283 experiences or reported being fine cycling on a short stretch of this road. Those who strongly disliked the arterial
 284 road reported avoiding this street as much as possible or preferred to cycle on the sidewalk instead. For example,
 285 the arterial road was perceived to be a “*speedway*” and an area that had “*a lot of car entitlement*”. Next, the left
 286 turn at a signalized intersection from an arterial road to a street with sharrows was disliked or concerning for

⁴This route was slightly adjusted for the audit. CycleStreets inferred that cyclists would cross midblock at an unsignalized intersection towards the end of the route. Cyclists have been found to be sensitive to intersections Broach et al. (2012). Therefore, the audited route was adjusted to a parallel street one block east that would enable a cyclist to cross at a signalized intersection.

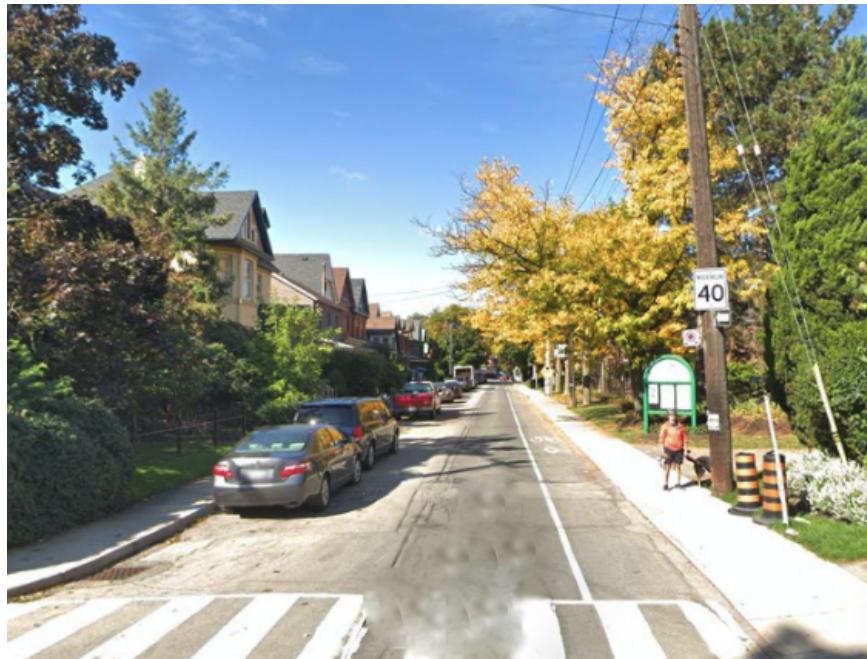


Figure 11: Segment 5 on route 2A depicting an on-street marked bicycle lane on a one-way street with one lane going westward. (Source: Google Street View)



Figure 12: Segment 18 of route 2A depicting the off-street multi-use path called the Hamilton Brantford Rail Trail. (Source: Google Street View)



Figure 13: Segment 8 of route 2A depicting the buffered bicycle lane ending and the transition that a cyclist would have to make to get into the left-turn lane. (Source: Google Street View)

287 some participants (see Figure 15). Many participants noted that they used an alternate route to get to the Rail
288 Trail to avoid this arterial road and intersection entirely.

289 Finally, most cyclists stated that they disliked an intersection at the end of the route that would require them
290 to transition from a residential to arterial road (see Figure 16). The area was viewed as very busy or “*not fluid*”
291 by some participants because there was an off-street multi-use path parallel to the road on the left side of the
292 roadway that could not be accessed swiftly from the right side. However, several participants reported that they
293 would have taken an alternate route to access the university campus from another entrance.

294 *3.2.2.2. Route 2B.* Some cyclists reported that they were familiar with this route or that they had previously
295 cycled part of the route. The participants commented that there was a mix of features of the route that they
296 liked and disliked. The segments along the route that were perceived to be “*quiet*” or “*residential*” were liked by
297 most participants because car volume and speed were perceived to be lower (see Figure 18). The protected off-
298 street multi-use trail over the highway was another feature that most participants liked or that elicited positive
299 comments (see Figure 19). In general, the segments that were perceived to not be busy with traffic were liked
300 or participants reported feeling comfortable cycling there, but the segments where car volume or speed were
301 perceived to be higher were disliked.

302 Some cyclists had mixed perceptions about the width of some of the segments (see Figure 20 and Figure 21). A
303 few participants commented that at times there appeared to be enough space for motorists to safely pass cyclists,
304 while others perceived the wide streets to potentially invite speeding. Anticipated car volume and the presence
305 of on-street parking along these segments seemed to influence perceptions about the width of the street and



Figure 14: Segment 14 of route 2A depicting an arterial road without on-street cycling infrastructure. (Source: Google Street View)



Figure 15: Segment 14 of route 2A depicting a signalized intersection where a cyclist would turn left on to a street with sharrows to travel to the Hamilton-Brantford Rail Trail. (Source: Google Street View)



Figure 16: Segment 29 of route 2A depicting the intersection of a residential road and two arterial roads. (Source: Google Street View)

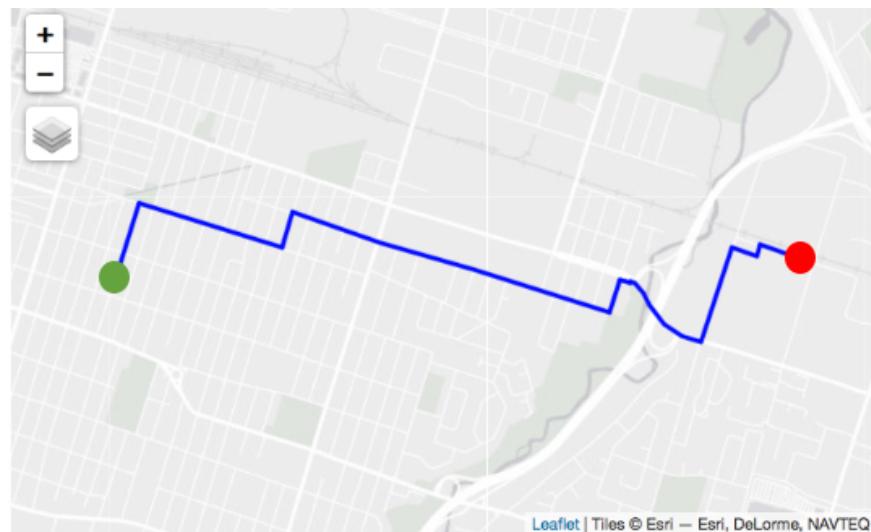


Figure 17: Map of route 2B.



Figure 18: Segment 11 of route 2B depicting a residential area. (Source: Google Street View)



Figure 19: Segment 30 of route 2B depicting the protected multi-use trail on the right side of the roadway on an arterial road over the Red Hill Valley Parkway. (Source: Google Street View)



Figure 20: Segment 14 on route 2B depicting a two-lane arterial road with on-street parking. (Source: Google Street View)

306 comfortability. Cyclists preferred to have space for a motorist to safely pass. Most participants noticed or disliked
307 the poor condition of the road along parts of the route. Finally, participants reported that they disliked the end
308 of the multi-use trail or having to cycle on an arterial road and cross four lanes to make a left turn (see Figure
309 22).

310 *3.2.3. Package 3*

311 *3.2.3.1. Route 3A*⁵. None of the participants had cycled in this area or were familiar with this route. The
312 opposite to Route 1A, participants liked the first half of the route and generally disliked features of the second
313 half. The beginning of the route was in a residential area; most cyclists reported that they liked the quiet streets
314 and good road condition (See Figure 24). The lower speed limit of 40 kilometres/hour was noticed by several
315 participants and some commented that they like travelling on streets with this speed limit. Once the route left
316 the residential area about mid-way, most participants disliked turning to or cycling on a two-lane arterial road
317 without infrastructure. The arterial road leading towards the industrial was perceived by some cyclists to be
318 designed for cars (see Figure 25 and Figure 26). One participant described this as, “*you’re just out on a bike in*
319 *the middle of the highway*”. The route ended in an industrial area which received mixed perceptions; some cyclists
320 commented that traffic volume did not appear to be too heavy in the photos while many others reported feeling
321 less comfortable cycling in an area where they could expect a lot of trucks.

⁵This route was slightly adjusted for the audit. The starting point was midblock on a residential street. The audit started instead at the nearest intersection along the route.



Figure 21: Segment 20 on route 2B depicting a two-lane arterial road with no on-street parking and a wide grassy verge on the right side of the roadway. (Source: Google Street View)



Figure 22: Segment 31 of route 2B depicting a lane change from the far right side of the roadway to the left-turn lane on a four-lane arterial road. (Source: Google Street View)

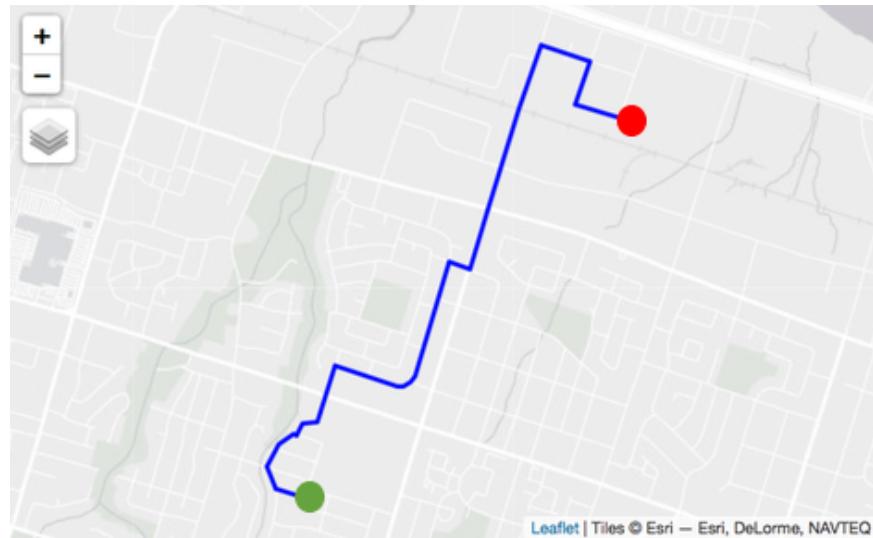


Figure 23: Map of route 3A.

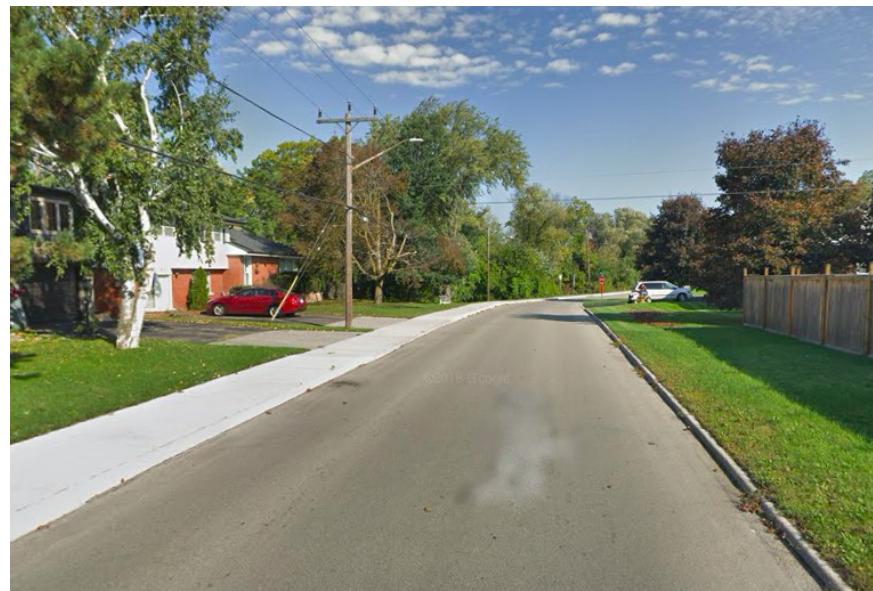


Figure 24: Segment 2 of route 3A depicting a residential street. (Source: Google Street View)



Figure 25: Segment 13 of route 3A depicting a two-lane arterial road without cycling facilities in a residential area. (Source: Google Street View)



Figure 26: Segment 15 of route 3A depicting a two-lane arterial road without cycling facilities or a sidewalk leading to a more industrial area. (Source: Google Street View)

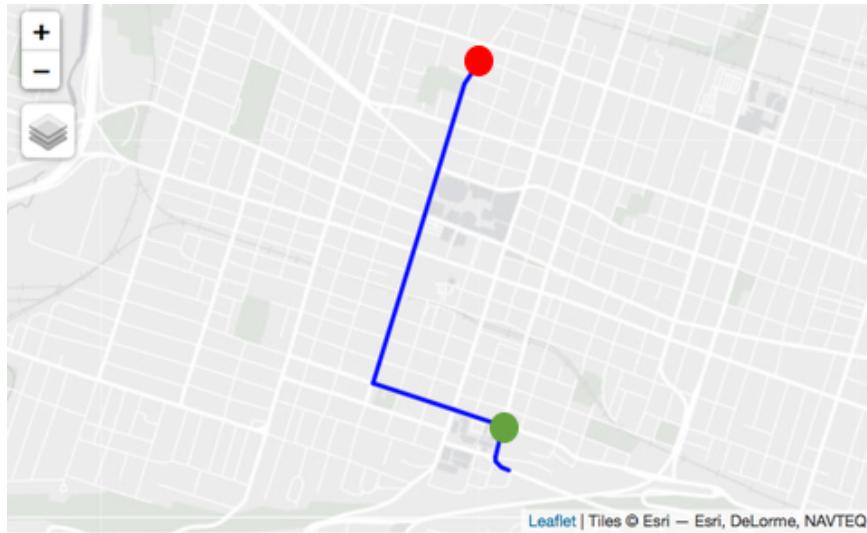


Figure 27: Map of route 3B.

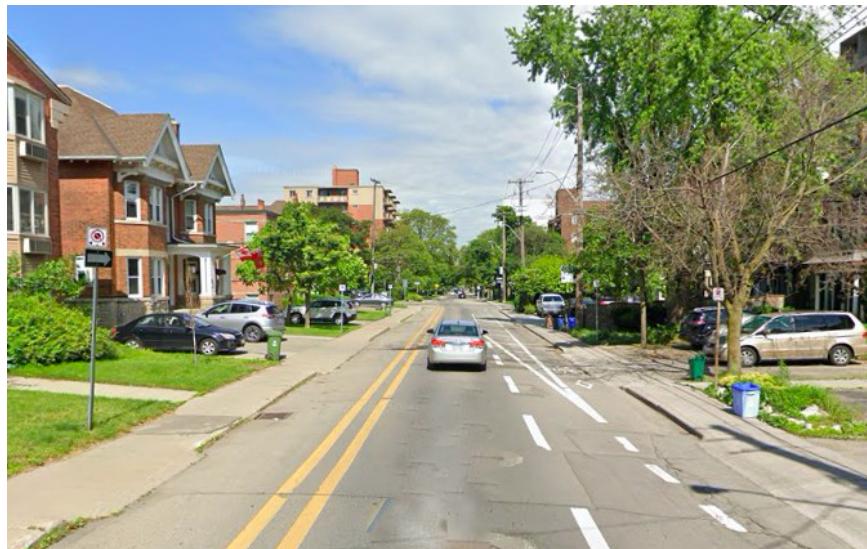


Figure 28: Segment 4 on route 3B with a buffered on-street bicycle lane on a one-way street. (Source: Google Street View)

322 3.2.3.2. *Route 3B*⁶. This route was familiar to the participants and the majority had cycled at least part of
 323 it. Cyclists liked that the majority of the route had cycling infrastructure (see Figure 28 and 29). The first few
 324 segments at the beginning of the route were perceived to be busy in terms of traffic by several participants, but
 325 many noted that people drive slower near the hospital.

326 The two-way cycle track (see Figure 29) was generally perceived well and elicited a lot of comments from
 327 participants, likely because they reported using it. However, participants expressed a mix of appreciation and
 328 frustration about this “*major cycling infrastructure*”. Several participants reported that they had witnessed

⁶This route was slightly adjusted for the audit. Rather than starting midblock on an uphill access to the escarpment, which would be an unlikely origin, the audit started two blocks south. Recall that the origin of each inferred route is the centroid of the traffic analysis zone, so this is not the true origin of this cycling flow.

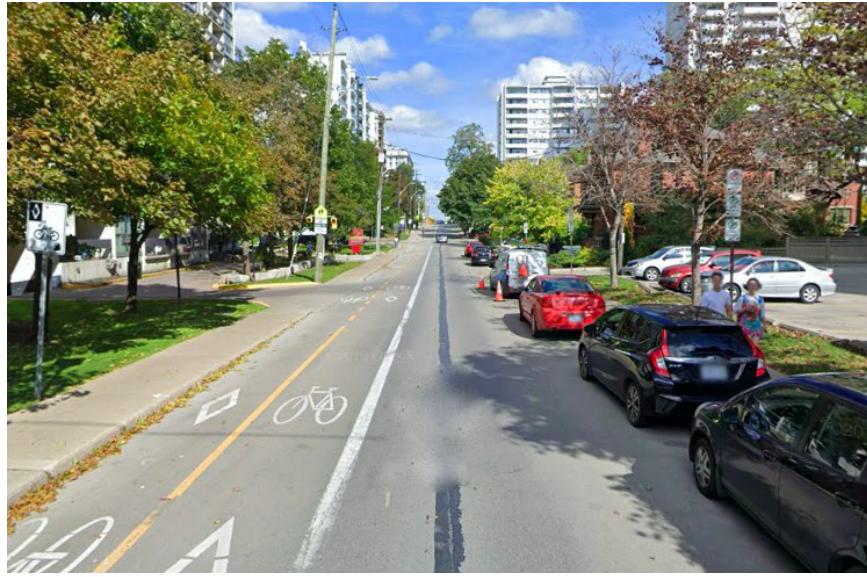


Figure 29: Segment 8 on route 3B depicting a two-way cycle track on a one-way arterial road. (Source: Google Street View)

329 people drive or park in the lanes, as well as drift into them to avoid passing closely to the parked cars in the
 330 outer right lane. Many participants expressed a desire to have enhanced protection along these facilities. Three
 331 participants, one travelling with a young child, reporting being hit by a motorist who was turning left across the
 332 cycle track. Others reported being vigilant when using this infrastructure because it is a two-way facility on a
 333 one-way street. Despite it being a relatively new and important North-South route in the city's cycling network,
 334 cyclists described that it needed improvements in particular areas that were conflict points with other road users.
 335 There were also mixed comments about a few intersections along the route that had bike boxes. Most cyclists
 336 reported that this infrastructure could be confusing, both for them and for motorists, and that sometimes
 337 motorists park in them if the light is red (see Figure 30). However, others reported that they liked the bike boxes
 338 and find them useful for transition points. The route was also perceived to be disconnected or disjointed by some
 339 participants; these comments were in reference to the different or inconsistent types of infrastructure along the
 340 route and because the infrastructure ends or is missing at certain spots.

341 3.3. Preferred Routes

342 After reviewing each of the three packages of photos, participants were asked to select which of the two routes
 343 in each package they preferred. All participants consistently selected the same routes: 1B was preferred over 1A,
 344 2A over 2B, and 3B over 3A. In the first package, cyclists preferred route 1B because they disliked the first three
 345 segments of 1A. Cycling on route 1B on residential streets was preferred over negotiating shared space on a busy
 346 four-lane arterial road even though there were dedicated cycling facilities later in the route. It is worth noting
 347 that a few participants commented that they most preferred the second half of 1A because it had an on-street
 348 marked bicycle lane, but that 1B was a better route overall. In the second package, participants preferred 2A
 349 because it had cycling infrastructure throughout compared to 2B which had a signed route only for part of it. 2A



Figure 30: Segment 20 of route 3B depicting the bike box at the intersection of two cycling facilities. After the intersection, the two-way cycle track on the left side of the roadway splits to on-street bicycle lanes on both sides of the road. (Source: Google Street View)

350 was also familiar to most participants. Finally, 3B was preferred for similar reasons that 2A was preferred; there
 351 were on-street cycling facilities for most of the route and it was familiar to most participants.

352 4. Discussion

353 The environmental audits revealed that each of the routes had a mix of attributes that support or hinder cycling.
 354 This can be expected in a city with a cycling network under development. The audits helped to explain why
 355 certain trip flows were over- or under-estimated by the model [paper submitted to *Transportation*]. All inferred
 356 routes included residential streets with lower volumes of cars or cycling infrastructure. With respect to the routes
 357 that were under-estimated (i.e., 1B, 2B, 3A, and 3B), there were many features that might influence cycling. For
 358 instance, two of the four (i.e., 2B and 3B) had some type of separated cycling facility. Three of the four routes
 359 (i.e., 1B, 2B, and 3A) included residential streets. Based on the routes audited, we observed that the *CycleStreets*
 360 algorithm makes sensible recommendations that a knowledgeable cyclist could take. Indeed, three of the six
 361 routes (1A, 2A, and 3B) were familiar to or had been previously cycled by many participants. This suggests that
 362 the inferred routes do match where cyclists actually travel in Hamilton.

363 Participants preferred routes that visibly accommodate cycling, and their route and infrastructure preferences
 364 align with previous literature. They preferred cycling facilities and streets with lower levels of traffic, which has
 365 been found in many other studies (*inter alia*, see Buehler and Dill, 2016; Clark et al., 2019; Mertens et al., 2017;
 366 Winters et al., 2011). Participants were also sensitive to traveling through intersections (Broach et al., 2012) and
 367 many enjoyed routes that had natural features (Marquart et al., 2020; Winters et al., 2011). Perceived car
 368 volume was another factor that participants frequently commented on as they reviewed photos, likely because
 369 cyclists are known to be sensitive to busy traffic (Segadilha and Sanches, 2014) and are motivated to cycle if
 370 there are routes away from cars (Winters et al., 2011). Cyclists in Hamilton describe similar experiences to those

371 who cycle in Waterloo, Ontario (Mayers and Glover, 2020), which suggests that a pattern of exclusion may
372 currently exist in mid-sized cities as they grapple with a tension between transport culture and new interventions.
373 Finally, participants also considered a range of factors beyond infrastructure to determine whether a street or
374 route sufficiently meets their needs and preferences, which is useful information for policy-makers and transport
375 planners. Many participants reported that they like to cycle on roads with smooth or good conditions, which has
376 previously been reported in the literature (Stinson and Bhat, 2003). Some cyclists preferred to have lateral space
377 to their right, like a sidewalk or some other “*escape zone*”, in the event that they needed to quickly move out of
378 the way. These attributes may be overlooked by transport planners but should be considered when planning
379 cycling networks and routes.

380 The temporal aspect of our photo elicitation approach also revealed that there is a threshold of unpleasantness
381 that cyclists are willing to tolerate along a route. In the case of route 1A, the segments along the arterial road
382 without infrastructure were such strong deterrents that cyclists preferred the other unfamiliar residential route.
383 Although 1A was inferred and not one that participants reported using, someone who is new to cycling but
384 unfamiliar with other routes could likely consider this to be the most direct route. The photo activity
385 underscored that the fragmented nature of the cycling network in a developing cycling city can create barriers for
386 accessing bikeable streets. This reinforces the importance of connected facilities in encouraging cycling (Buehler
387 and Dill, 2016; Handy, 2020; Yang et al., 2019) and that navigating mixed traffic in cities where there is less
388 infrastructure is perceived to be less safe (Chataway et al., 2014). More importantly, these streets are not
389 separate from the rest of the transport system and the ability to reach this infrastructure matters. If getting to
390 on-street cycling facilities is perceived to be challenging or too dangerous, then regular and even potential cyclists
391 may be unwilling to use existing infrastructure or avoid routes that incorporate these streets altogether.

392 4.1. Policy Implications

393 There are three important implications of this study for developing cycling cities: i) the perceptions of cyclists
394 should be regularly explored and incorporated in route design; ii) the timing of incorporating cyclists’ feedback is
395 important for ensuring that infrastructure is functional and adapted as it grows; and iii) using photo elicitation is
396 an innovative and practical approach for planning practice.

397 Although our approach differed from other studies where participants took photos themselves (Guell and Ogilvie,
398 2015; Ward et al., 2015), the photo activity was illuminating because it helped participants recall their
399 experiences and revealed rich insights about cycling behaviours and perceptions. This evidence could not have
400 been derived from a travel survey or cycle routing algorithm. This is one of the benefits of using photos to elicit
401 dialogue because they “evoke deeper elements of human consciousness than do words” (Harper, 2002). Therefore,
402 it is recommended that developing cycling cities routinely examine cycling perceptions through qualitative data
403 like photo elicitation to centre the experience of cycling in the design of infrastructure and routes. This data can
404 also be useful for mobile applications based on crowdsourced data or digital platforms that incorporate cyclists’

405 informal routes to inform future cycling route and new locations for infrastructure (see Cellina et al., 2020;
406 Meireles and Ribeiro, 2020). Users can describe how particular routes or types of infrastructure are actually
407 experienced and travelled, both to communicate preferred routes to other cyclists and to highlight necessary
408 improvements to planners. The use of photos can extend current planning practices beyond simple identification
409 of problem areas by describing how cyclists navigate these spaces.

410 Furthermore, inviting cyclists to have a more regular participatory role in route design and planning as the
411 cycling network develops is an important practice. Failing to understand and integrate cyclists' perceptions and
412 preferences in planning early on in a city's cycling network development can negatively impact efforts to increase
413 cycling; resources could be spent on facilities that are fundamentally unappealing to cyclists or other barriers can
414 be ignored. Taking advantage of cyclists' expertise in developing cycling cities can help to overcome the barrier of
415 a lack of safe cycling routes, a barrier identified in another "low cycling maturity" city by Félix et al. (2019).
416 Marquart et al.'s (2020) study highlights that planners "are determining the characteristics of routes in urban
417 areas", which supports our recommendation that more opportunities be created for cyclists to share feedback.
418 Without such opportunities, tools can be developed that only reflect the designers' perceptions and that fail to
419 account for the needs of other cyclists like women (Xie and Spinney, 2018). Participants' comments about the
420 bike boxes, a relatively new cycling intervention in Hamilton, is one example of how the use of photos and
421 detailed feedback can be informative for transport planners. Likewise, new or potential cyclists also have specific
422 preferences and their perceptions should be explored through similar approaches. In addition to our methods,
423 other mapping techniques (see Manton et al., 2016; Marquart et al., 2020), ride-along activities (see van Duppen
424 and Spierings, 2013), and frequent audits before and after next infrastructure is built may be further informative
425 for understanding how cyclists navigate developing cycling cities.

426 Finally, transport planners in developing cycling cities, like Hamilton, should make every effort to focus beyond
427 infrastructure and seek to better integrate these individual links within a transport system that is designed with
428 pro-cycling policies in mind. Studies have provided evidence that cities that are most successful in increasing
429 their cycling trips and levels have implemented a suite of interventions to change behaviour and the built
430 environment (Pucher et al., 2011, 2010). Our findings support the recommendation that the City of Hamilton
431 explore and implement bolder policies to encourage modal shifts. There is strong incentive for prioritizing cycling
432 more: 35% of all current trips in Hamilton could be cycled (Mitra et al., 2016) and more people could benefit
433 from increased physical activity.

434 5. Study Limitations

435 There are some instances where the *CycleStreets* algorithm failed to include some of the city's off-street cycle
436 infrastructure or signed routes. Some participants noted these situations and described alternate detours that are
437 more locally known. This highlights that a routing algorithm may not reflect the extent or range of behaviours

438 of cyclists. However, many routes were familiar to participants so we find that the algorithm makes sensible
439 recommendations. Although the photos of the routes were taken from Google Street View and may not reflect
440 prime cycling times and likely traffic volumes expected at those times, there were no errors or differences pointed
441 out by participants along routes familiar to them.

442 Furthermore, several cyclists noted that the routes they preferred were familiar to them, which suggests that
443 familiarity played a role in their decision. This makes sense because it affords them more intimate knowledge of
444 the route. Therefore, our findings could have been different if the participants were familiar with all of the routes
445 or if they were familiar with none. However, their familiarity offered insightful information about how these road
446 spaces are actually experienced which is useful for transport planners in Hamilton. Our findings would also likely
447 have been different if the participants were new or occasional cyclists. Less experienced cyclists are likely to have
448 even stronger preferences for protected infrastructure and be more averse to mixing with traffic (Winters et al.,
449 2011). The findings may not match the preferences or experiences of other cyclists such as older adults, women
450 who are more conscious of traffic risks, children, or marginalized groups. These individuals have unique needs
451 with respect to separation from traffic and perceptions of the built environment, as well as different trip patterns
452 (*inter alia* see Aldred, 2015; Black and Street, 2014; Emond et al., 2009).

453 Finally, some photos taken from Google Street View were darker or cloudier than others. This was noticed by
454 some participants, suggesting that it may have subconsciously influenced participants' perceptions. However,
455 there was similarity in participants' stated preferences and all selected the same preferred routes. This suggests
456 the weather depicted in the photos likely had less of an influence on individual perceptions and preferences, and
457 that attributes of the routes and familiarity were more important.

458 6. Conclusion

459 Through environmental audits and a photo activity in semi-structured interviews we demonstrated that cycling
460 routes in Hamilton have a mix of attributes that support and hinder cycling. The interviews with regular cyclists
461 revealed that they prefer routes that have dedicated cycling infrastructure or streets with low volumes of traffic,
462 and that existing infrastructure needs to be adapted to better align with cyclists' needs and preferences. As a
463 developing cycling city with 46% of the cycling network completed, the findings from this study will be useful to
464 policy-makers and transport planners in Hamilton, and other mid-sized cities with growing cycling levels, to
465 design more bicycle-friendly streets and facilitate more trips that enable people to be physically active. Our
466 findings support the recommendation that other developing cycling cities involve local cyclists to inform
467 infrastructure design and location and pay attention to a broad range of built environment factors that influence
468 where people choose to cycle. The use of photos to explore cyclists' perceptions and experiences is a promising
469 participatory approach that can be incorporated into planning practice to complement travel survey data and
470 better centre the cycling experience in cycle infrastructure and route design.

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476 2018), **dplyr** (Wickham et al., 2021), **float** (Schmidt and Chen, 2020), **forcats** (Wickham, 2020), **ggplot2**
477 (Wickham et al., 2020), **ggthemes** (Arnold, 2019), **kableExtra** (Zhu, 2020), **knitr** (Xie, 2021), **ngram** (Schmidt
478 and Heckendorf, 2017), **purrr** (Henry and Wickham, 2020), **readr** (Wickham and Hester, 2020), **rticles** (Allaire
479 et al., 2021), **sf** (Pebesma, 2021), **sp** (Pebesma and Bivand, 2021), **spdep** (Bivand, 2020).

480 **8. CRediT Statement**

481 **First author:** conceptualization, methodology, investigation, formal analysis, data curation, writing - original
482 draft, writing - review & editing. **Second author:** conceptualization, methodology, writing - original draft,
483 writing - review & editing. **Third author:** conceptualization, writing - original draft, writing - review & editing.
484 **Fourth author:** conceptualization, writing - original draft, writing - review & editing. **Fifth author:**
485 conceptualization, methodology, writing - original draft, writing - review & editing, supervision.

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