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Intersections as Barriers to Low-Stress Cycling: Intersection Level of Traffic Stress and Dual-Graph Network Modeling

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Dear Editors,

We are pleased to submit our manuscript, *"Intersections as Barriers to Low-Stress Cycling: Intersection Level of Traffic Stress and Dual-Graph Network Modeling,"* for consideration in the Journal of Transport Geography.

This paper addresses a long-standing gap in bicycle network analysis: the absence of a method for incorporating intersection crossing stress into low-stress routing and accessibility evaluation. We propose a comprehensive set of criteria for Crossing Level of Traffic Stress (xLTS), covering signalized and unsignalized intersections, freeway ramp crossings, and special geometric conditions. We also show how the dual graph network representation can be adapted to enforce both segment and intersection stress constraints in shortest-path algorithms.

Through case studies in Montreal and Boston, we identify critical crossings — intersections where crossing stress exceeds the stress on both the approach and departure segments — and demonstrate their impact on bicycle accessibility to jobs. In Boston, enforcing crossing stress reduces LTS 1 job accessibility by more than 75%, confirming that intersections are a major barrier to cycling for children and stress-sensitive adults.

We believe this paper is well suited to JTG given the journal's focus on geographic and network dimensions of transport. The methodology is directly applicable to planning practice, and the results offer insights relevant to any city seeking to evaluate and improve low-stress bicycle network connectivity.

This manuscript has not been previously published and is not under consideration elsewhere. All authors have approved the submission.

Best regards,

Nathan David Obeng-Amoako

On behalf of all authors

Intersections as Barriers to Low-Stress Cycling: Intersection Level of Traffic Stress and Dual-Graph Network Modeling

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Keywords: bicycle accessibility; level of traffic stress; intersection model; bicycle network; dual graph.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions (CRediT)

Peter G. Furth: Conceptualization; Methodology; Writing – Original Draft; Writing – Review & Editing; Supervision

Nathan David Obeng-Amoako: Software; Data Curation; Formal Analysis; Visualization; Writing – Original Draft; Writing – Review & Editing

Armin Akhavan: Conceptualization; Methodology; Software

Bita Sadeghinasr: Data Curation; Formal Analysis; Software

Ray Saeidi: Methodology; Data Curation; Software

Luis Miranda-Moreno: Methodology; Project Administration; Funding Acquisition
Christine Théberge-Barrette: Data Curation; Validation
Paul Moser: Conceptualization; Methodology; Project Administration; Funding Acquisition
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Intersections as Barriers to Low-Stress Cycling: Intersection Level of Traffic Stress and Dual-Graph Network Modeling

ABSTRACT

While it is widely recognized that intersections, like road segments, involve traffic stress that can be a barrier to cycling, bicycle network analysis has lacked a method for incorporating intersection crossing stress into bicyclist routing and accessibility analyses. Criteria for crossing level of traffic stress (xLTS) are proposed for both signalized and unsignalized intersections. For unsignalized intersections, a large set of critical factors – the number of lanes being crossed, traffic volume and speed on the crossed street, presence of a crossing island, and characteristics of the crosser – are merged in a gap acceptance model because the same factors that force one to wait a long time to cross safely also make it stressful to cross. For network analysis, we show how the dual graph approach, long used with vehicle routing to model turn penalties, can be adapted for bicycle routing with intersection LTS. In this approach, cyclists are routed, not from node to node, but from the end of one link to the end of the next link, with dual edges holding the distance traveled, link LTS, and turning movement LTS. A case study in Boston finds that at LTS 1, the percentage of jobs accessible to residents falls from 0.9% to 0.2% when crossing stress is accounted for while at LTS 2, it falls from 12.1% to 10.9%, demonstrating how intersection traffic stress functions as a barrier to low-stress cycling. This paper fills a methodological gap by making intersection stress measurable in low-stress bicycle accessibility analyses.

Keywords: bicycle accessibility; level of traffic stress; intersection model; bicycle network; dual graph.

1. BACKGROUND AND OBJECTIVES

The Level of Traffic Stress (LTS) framework (Furth et al., 2016; Mekuria et al., 2012) operationalizes the premise that most people will cycle only on routes free of threatening traffic conditions. It classifies cyclists on a four-level scale — LTS 1 (children and stress-sensitive adults) through LTS 4 (most assertive cyclists) — and assigns a stress level to each road segment based on road characteristics and infrastructure. For routing and accessibility, cyclists tolerating LTS k are restricted to segments rated k or below, with route stress governed by a weakest-link principle.

Excluding high-stress links often fragments the network, leaving many origin-destination pairs disconnected. Mekuria et al. (2012) found that only 0.4% of home-to-work trips up to six miles were connected at LTS 1 in San Jose, rising to 4.7% at LTS 2 and 16.4% at LTS 3. Furth et al. (2018) introduced a propensity-based measure of bike-accessible jobs in northern Delaware, showing how low-stress connectivity can serve as a planning metric. Subsequent studies extended the approach: Lowry and Loh (2017) found a positive correlation between low-stress connectivity and observed cycling trips across 28 Seattle neighborhoods; Murphy and Owen (2019) computed jobs accessibility on LTS-filtered networks across four U.S. metros, finding reduced accessibility universally under low-stress constraints; Faghih Imani et al. (2019) showed that low-stress jobs accessibility was a statistically significant predictor of cycling mode choice in Toronto; and Ahmadi et al. (2026) applied LTS analysis to school access for young people in Montreal.

Intersections can also be stressful enough to deter cyclists, with a single high-stress crossing capable of negating miles of low-stress segments. Using GPS data from 164 Portland cyclists, Broach et al. (2012) found that cyclists accept meaningful detour to avoid high-stress crossings. A review of revealed and stated preference studies confirmed that intersections negatively affect the cycling experience (Buehler and Dill, 2016), and federal guidance has acknowledged that an otherwise high-quality facility is of limited use if a high-stress crossing blocks the route (Twaddell et al., 2018).

Typical network analysis treats intersections as costless pass-through points. Incorporating intersection crossing stress requires two things: first, crossing stress criteria spanning all intersection types (signalized, unsignalized, ramp terminals), calibrated to the same four LTS classes as segment stress; second, new network modeling structures, since the conventional graph — where nodes are intersections and edges are segments — has no natural place to attach movement-level costs. This requires transforming the network so that turning movement constraints can be handled in a shortest path algorithm.

This paper addresses both needs with five contributions. First, we show that all cyclist intersection movements can be decomposed into simple single-leg crossings, so that stress criteria are needed only for simple crossings rather than every possible movement. Second, we propose comprehensive criteria for Crossing Level of Traffic Stress (xLTS), covering signalized and unsignalized crossings and special conditions including freeway ramps. Third, we introduce the concept of critical crossings — crossings where stress exceeds that of both the approach and departure segment, and which should be prioritized for treatment. Fourth, we show how a dual graph representation — directed segments as nodes, permitted movements as edges — enables standard shortest-path algorithms to enforce both segment and crossing stress constraints, with correct handling of one-way streets, divided roads, and turn prohibitions. Fifth, we demonstrate empirically that omitting crossing stress from bicycle network analysis can materially understate barriers facing cyclists. The remainder of the paper covers prior research on intersection stress modeling, the proposed xLTS criteria, the dual graph representation, case study settings and data for Montreal and Boston, results, discussion, and conclusions.

2. LITERATURE REVIEW – INTERSECTION STRESSORS

Signalized Intersections

Landis et al. (2003) developed a level-of-service model for cyclists at signalized intersections, identifying traffic volume, outside lane width, and crossing distance as primary stress factors. For pedestrians, Petritsch et al. (2005) found permitted left-turn and right-turn-on-red volumes to be dominant stressors alongside number of lanes and delay, as these movements are less predictable than signal-controlled through traffic. Macro-level safety indices by Carter et al. (2007) and Zegeer et al. (2006) consistently identified volume, speed, number of lanes, and turning conflicts as dominant risk factors across multiple U.S. cities, with bike lane presence and continuity also significant for cyclists. Steinman and Hines (2004) further showed that dominant stressors differ by mode: crossing distance and turning conflicts for pedestrians, physical separation and signal phasing for cyclists.

Long crossings can be stressful if cyclists cannot clear the intersection before conflicting traffic is released. Shladover et al. (2009) found conventional signal timing based on vehicle speeds can fail to provide sufficient cyclist clearance time. NCHRP Report 969 (2022) recommends adjusting minimum green formulas accordingly, adopted by some states, but protection for late-green arrivals remains rare since red clearance intervals in the U.S. are nearly universally based on auto speed.

Permitted turning vehicles are a persistent crash source. Right hook and left cross crashes are long-recognized dominant crash types (Hunter et al., 1995). Preusser et al. (1981) found right-turn-on-red increased pedestrian crashes 43–107% and bicycle crashes 72–123%. Permitted left turns pose perhaps the greatest risk: Petritsch et al. (2005) identified permitted left-turn volume as a primary stressor. *Boston Transportation Department Signal Operations Design Policy (2023)* requires protected-only left-turn phasing above 1.5 vehicles per cycle and protected-only right-turn phasing above 5.5 vehicles per cycle.

Unsignalized Intersections

At unsignalized crossings, crash risk and severity increase with number of lanes, speed, and volume on the crossed road. Zegeer et al. (2005) found pedestrian crash rates substantially higher on multilane roads, with serious and fatal injuries concentrated at wider, higher-speed crossings. Two treatments substantially reduce crossing stress: raised medians reduced pedestrian crashes by 46% at marked crossings and 39% at unmarked ones by enabling staged crossings; and rectangular rapid flashing beacons (RRFBs) produced driver yielding rates as high as 98% at multilane uncontrolled crosswalks compared to under 20% without beacons, with no habituation over 14 months (Shurbutt and Van Houten, 2010).

The original LTS study (Mekuria et al., 2012) proposed two intersection-related criteria: one for pocket bike lanes (better classified as a segment-level criterion) and one for unsignalized crossings based on speed and number of lanes, which this paper refines. Some applications have equated crossing stress with the LTS of the crossed road (Huertas et al., 2020), but this conflates two distinct conditions — a busy road with protected bike lanes may be easy to ride but stressful to cross, while a signal can make a busy road easy to cross regardless of its segment LTS.

Slip Lane and Ramp Crossings

Slip lane crossings are typically unsignalized even at signalized intersections, with high turning speeds and driver attention directed toward merging rather than yielding. O'Brien et al. (2012) found that 79% of slip-lane crashes in Melbourne involved pedestrians approaching from the sidewalk, the direction least likely to be checked when scanning for gaps. Potts et al. (2013) confirmed that slip lane crossings warrant independent assessment rather than treatment as part of the main intersection. Freeway ramp crossings compound these hazards: vehicles cross the bike path at near-freeway speeds, and the shallow geometry of entrance ramps can cause drivers to fail to recognize they are turning and have an obligation to yield.

3. CROSSING LTS (xLTS) AND MOVEMENT LTS (mLTS)

A crossing is defined as the movement across one leg of an intersection, where a leg is a roadway including traffic in both directions. Crossing stress depends on the leg's traffic volume, speed, crossing distance, and traffic control. This is abbreviated xLTS. For network analysis, however, what matters is movement LTS (mLTS): the stress of every possible cyclist movement at an intersection — through, left, or right. Each movement can be decomposed into a series of crossings proceeding counterclockwise around the intersection (**Figure 1**). At a standard crossroads, a right turn involves no crossings, a through movement involves one, and a left turn involves two. Following the weakest-link principle, mLTS is the maximum xLTS among all crossings in the movement. Right turns, involving no crossing, have mLTS = 1. This is summarized in **Equation (1)**.

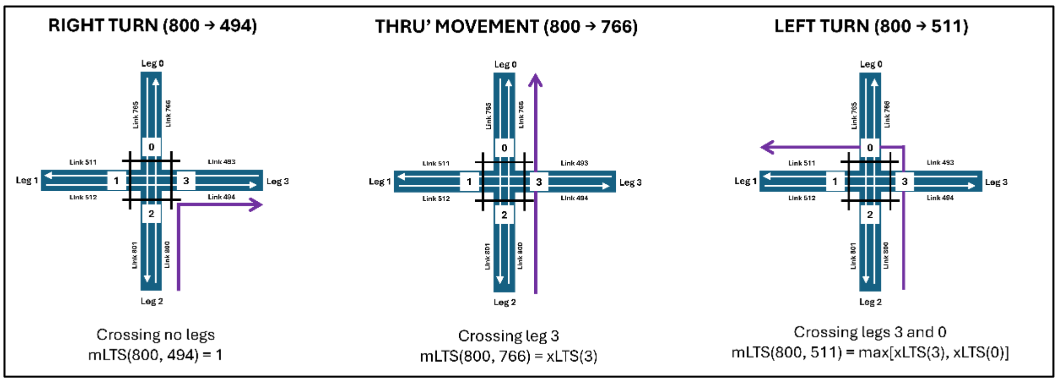


Figure 1. Relationship between intersection movements and crossings, and between movement LTS (mLTS) and crossing LTS (xLTS), at a four-leg intersection.

$$mLTS(a, b, I) = max\{1, xLTS(k): k \in legs\ between\ a\ and\ b\} \quad \textbf{(1)}$$

where

$xLTS(k)$ = LTS of crossing leg k

$mLTS(a, b, I)$ = LTS of the movement from link a to link b at intersection I

"legs between a and b" are the legs encountered when rotating counterclockwise from the leg containing a to the leg containing b, exclusive of start and end leg.

If there are no intervening legs, as with a right turn, $mLTS(a, b, I)$ = 1.

Decomposing turning movements into crossings simplifies modeling by requiring stress criteria only for simple crossings rather than every movement type. While this assumes pedestrian-style left turns, it does not distort routing for cyclists who make vehicular left turns, since vehicular left turns are almost always more stressful and any cyclist willing to make one can certainly tolerate the equivalent pedestrian-style turn.

4. CRITERIA FOR CROSSING STRESS

Criteria were developed based on factors known to create traffic stress and crash risk, and in consultation with bicycle planners in Delaware, Montreal, and Boston. As with segment-level LTS, planners may adjust xLTS criteria to reflect local policies, data limitations, and priorities. Criteria cover signalized crossings, unsignalized crossings, freeway ramp crossings, and crossings with poor sight lines.

4.1 Crossing Stress Triggers at Signalized Intersections

By default, xLTS = 1 at signalized crossings since a signal provides a protected interval with conflicting traffic stopped. However, certain conditions trigger elevated stress, as given in **Table 1**, whether cyclists are in mixed traffic, a conventional bike lane, or a protected bike lane. Triggers can increase but never decrease stress. LTS 2 triggers indicate conditions unacceptable for most child cyclists; LTS 3 triggers indicate stress unacceptable to most adults.

Long crossings are stressful because clearance intervals are generally timed for auto speeds, potentially releasing conflicting traffic while cyclists are still in the intersection. A bike signal eliminates this concern.

Volume limits for permitted turn conflicts follow *Boston Transportation Department Signal Operations Design Policy, (2023)*. Higher right-turn conflict volumes are permitted where bike boxes or head-start timing eliminate most early-phase conflicts. The speed trigger applies mainly at skew intersections lacking signal separation.

Crossing LTS is elevated when cyclists must cross in two or more stages and wait in a traffic island, unless the median is at least 30 m deep, in which case the stages are treated as two distinct crossings.

Near signalized intersections, bike lanes are sometimes converted to pocket lanes (sandwiched between a through lane and a right-turn lane) or mixing zones (right-turn lanes shared with through cyclists). Stress from these treatments applies to the road segment rather than the crossing, since it affects even right-turning cyclists. Trigger criteria are given in

Table 2; pocket lane criteria are unchanged from (Mekuria et al., 2012).

4.2 Unsignalized Intersections

At unsignalized intersections, priority approaches have no crossing stress (xLTS = 1). For non-priority approaches, xLTS criteria are given in **Figure 2** as a function of cross-street lanes, average daily traffic (ADT), and 85th percentile speed, with credit for a crossing island. This refines Mekuria et al. (2012) by adding volume as a factor.

Volume thresholds were derived from gap acceptance theory (Tian et al., 2022), assuming Poisson-distributed arrivals during a peak hour at 8.3% of ADT. Where safe gaps are rare, cyclists wait longer and are more likely to attempt risky crossings; conversely, frequent gaps imply longer comfortable gaps as well. The factors governing gap availability are thus the same as those governing crossing stress.

A safe gap was defined as sufficient time to cross at a below-average cyclist speed, plus start-up offset and a comfortable post-encroachment time. Parameter values (**Table 3**) vary by LTS to reflect different user types: LTS 1 (children) uses lower speed, greater start-up offset, and greater post-encroachment time; LTS 3 (enthusiasts) uses higher speed and lower start-up offset. For a two-lane road at 25 mph, the required gap is 8.9 s at xLTS 1 versus 6.4 s at xLTS 2 and 3.

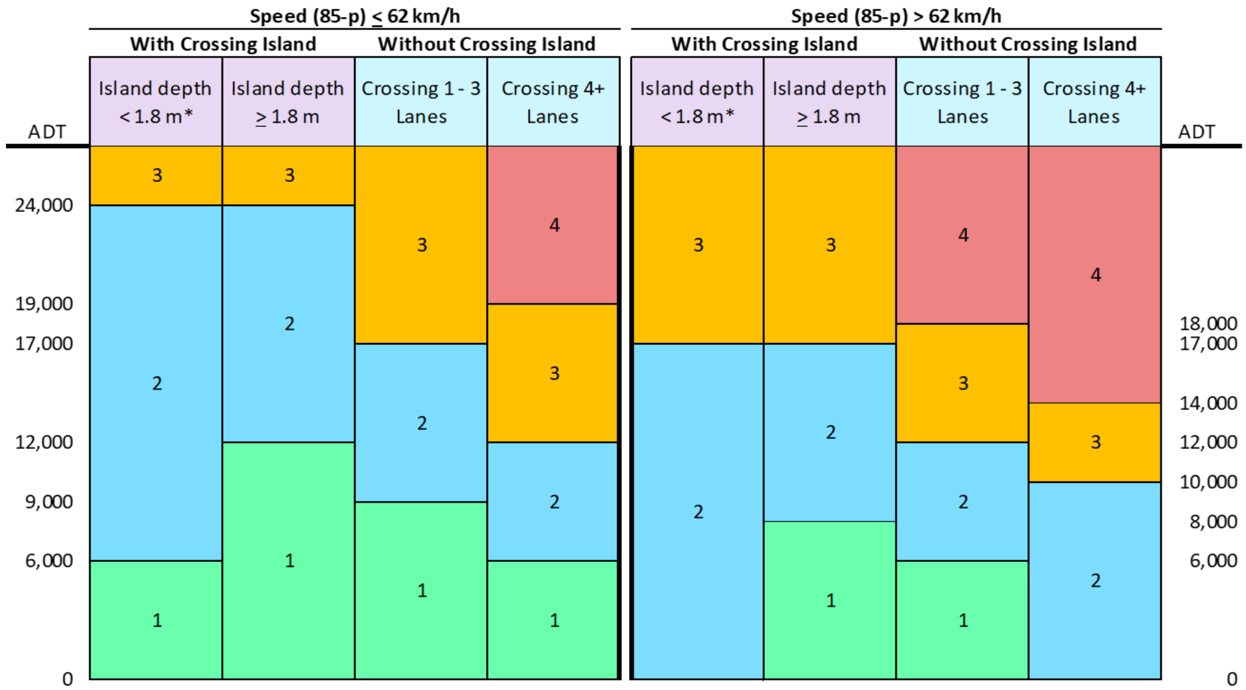
The acceptable delay threshold also varies by LTS, with lower thresholds for lower stress levels. The higher LTS 3 threshold compensates for the unrealism of Poisson arrivals under heavy traffic, which tends to form platoons that create additional gaps not captured by the Poisson model.

Table 1. xLTS triggers for signalized intersection crossings.

Factor	Condition	xLTS 2 trigger	xLTS 3 trigger
Crossing distance	There is no bike signal and no crossing island at least 1.8 m (6 ft) deep	crossing distance > 30 m (100 ft)	
Permitted right turn volume, peak hour	A bike box or head-start interval is provided	volume > 5.5 per cycle (or 200/h where cycle length is unknown)	
	Otherwise	volume > 3.5 per cycle (or 120/h where cycle length is unknown)	
Permitted left turn volume, peak hour	Multilane road (2 or more thru lanes) whose left turns have a permitted conflict with the bike crossing	volume > 1.5 per cycle (or 50/h where cycle length is unknown)	
Permitted right turn speed	Right turns that have a permitted conflict with the bike crossing	speed > 24 km/h (15 mph)	> 35 km/h (22 mph)
Multistage crossing	Bikes make their crossing in 2 or more stages, waiting for the next stage in a crossing island	Crossing island depth < 30 m (100 ft)	

Table 2. Segment LTS triggers where a bike lane is converted to a pocket bike lane or mixing zone.

Treatment	Calm conflict condition – apply segment LTS 2	If calm conflict condition isn't met:
Pocket bike lane	Right-turn lane begins abruptly to right of bike lane, AND bike lane continues straight AND lane length ≤ 50 m AND right-turn radius ≤ 12 m	Apply segment LTS criteria for Mixed Traffic
Mixing zone	Mixing zone length < 50 m AND right-turn radius ≤ 12 m	Apply segment LTS criteria for Mixed Traffic



** A crossing island cannot increase xLTS. If a shallow island (< 1.8 m) is present and the road has only 2 or 3 lanes, use the minimum of {xLTS with island, xLTS without island}.*

Figure 2. xLTS for unsignalized non-priority crossings.

Table 3. Parameters of needed gap length by user class.

User class	**Speed (ft/s)**	**Start-up offset (s)**	**Post-encroachment time (s) by traffic speed**				**Maximum average delay (s)**
			≤ 30 mph	**35 mph**	**45 mph**	**55 mph**	
LTS 1 (children)	8.8	4.4	2.0	25	4.3	5.8	25
LTS 2 (most adults)	11.0	3.4	1.0	35	2.5	3.5	35
LTS 3 (bike enthusiasts)	14.7	2.4	1.0	180	2.5	3.5	180

Crossing islands, even informal ones under 6 ft deep, reduce crossing stress by enabling staged crossings. **Figure 2** columns with island presence assume a 4-lane crossing; for 2-3 lane crossings with an island, use the lower of the island and no-island stress values.

4.3 Trail Crossings

Where a stand-alone bicycle path crosses a one-lane-per-direction road with no parallel vehicular traffic, motorists are likely to yield under conditions specified in **Table 4**. Trail crossings meeting these conditions have xLTS = 1; otherwise, they are treated as standard unsignalized crossings using **Figure 2**.

Table 4. xLTS for trail crossings of unsignalized roads with one lane* per direction

RRFB?	ADT	Speed ≤ 46 km/h		46 km/h < Speed ≤ 62 km/h		Speed > 62 km/h
		With island	No island	With island	No island	
With RRFB	Any	xLTS 1	xLTS 1	xLTS 1	xLTS 1	Use Figure 2
No RRFB	≤ 8,000	xLTS 1	xLTS 1	xLTS 1	xLTS 1	Use Figure 2
	> 8,000	xLTS 1	Use Figure 2	Use Figure 2	Use Figure 2	Use Figure 2

* For roads with more than one lane per direction, use **Figure 2**.

4.4 Freeway Ramp Junctions and Crossings with Blind Entry

Freeway ramp crossings are especially stressful due to high volume and speed. Off-ramp crossings are less stressful than on-ramp crossings since drivers approaching an off-ramp are already in a yielding mindset. xLTS criteria are given in **Table 5**, which also covers blind entries — situations where path and intersection geometry requires cyclists to look behind them for conflicting vehicles, as illustrated in **Figure 3**.

5. DUAL GRAPH REPRESENTATION

In the standard graph representation of a street network, intersections are nodes and road segments are directed edges. This works well when all costs apply to segments, but cannot support costs or constraints on intersection movements — any cost applied to a node applies equally to every movement through it regardless of direction. The seminal LTS study (Mekuria et al., 2012) used a workaround that applied crossing stress to approach segments, but this distorts routing by penalizing cyclists on the approach segment who are not making the crossing, including right-turners and those with origins or destinations on that segment. The dual graph resolves this by inverting the representation: directed segments become nodes and intersection movements become edges. Dual edges carry attributes for both segment stress and movement stress, so filtering edges by stress tolerance removes high-stress crossings and high-stress segments without distortion.

Table 5. xLTS triggers for freeway ramp conflicts and blind entry hazards

Factor	Condition	xLTS 2 Trigger	xLTS 3 Trigger
Crossing an on-ramp (ramp from bicycling road to freeway)	Does not apply where conflicting traffic has a stop sign	Departure road 85th percentile speed ≤ 54 km/h OR road geometry requires ramp entry speed ≤ 24 km/h	Other on-ramp crossing
Crossing an off-ramp (ramp from freeway to bicycling road)	Does not apply where conflicting traffic has a stop sign	Receiving road 85th percentile speed ≤ 62 km/h OR ramp speed at crossing ≥ 50 km/h OR crossing crosses ramp at a right angle	Other off-ramp crossing
Blind entry hazard		Cyclists enter a crossing from a path abutting the roadway, requiring them to look backwards to scan for conflicting traffic	—

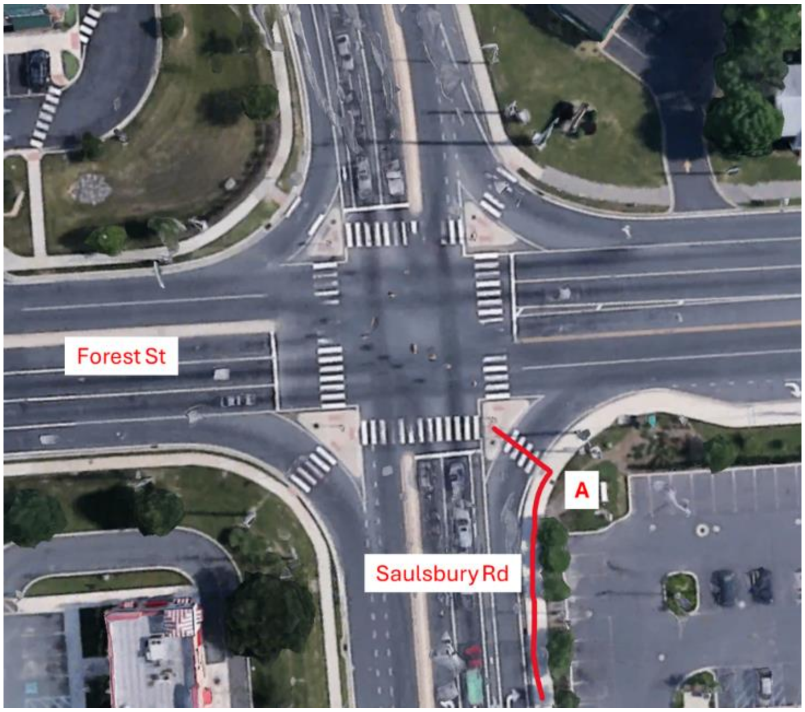


Figure 3. Blind entry hazard at an intersection in Dover, DE due to a sidepath abutting a roadway at a crossing, requiring cyclists to look backward to check for conflicting vehicles.

The dual graph has a long history in transportation. Caldwell (1961) identified that turn penalties require a formulation where segment transitions carry cost. Kirby and Potts (1969) formalized this as the minimum route problem. Añez et al. (1996) introduced the dual graph as a systematic solution, showing that turn prohibitions can be enforced simply by omitting the corresponding dual edge. Winter (2002) extended it to arbitrary movement-level costs. Despite this foundation, bicycle network analysis has not adopted the dual graph until now — Boeing's OSMnx, the dominant open-source tool, constructs primal networks with no mechanism for movement-level attributes, and prior LTS studies have operated within the same limitation. This paper adapts the dual graph to LTS-constrained bicycle network analysis, with new data structures described below.

5.1 Data Structures

5.1.1 Centerline and Dual-Line Road Representation

U.S. road networks often represent some two-way roads as centerlines and others as pairs of unidirectional lines. The data structures developed here accommodate this mix, though the dual graph ultimately requires all bidirectional segments to be converted to unidirectional pairs.

5.1.2 Intersections

Intersections are the fundamental unit of dual graph construction, defining dual edges and distinguishing internal from external segments. They are also the unit of signalization — traffic signal data in GIS are typically associated with intersections rather than individual links.

Physically, an intersection is where two or more roads meet. As shown in **Figure 4**, the number of nodes representing an intersection varies: one node for centerline roads, multiple nodes where divided carriageways are used. An intersection is therefore defined as a cluster of nodes. Clusters are identified by finding pairs of nodes within a calibrated distance threshold where at least one connects to a divided-road link; those nodes are merged into a single intersection object at their geometric centroid. The threshold was calibrated empirically against observed carriageway separations, set large enough to capture all cases while keeping false positives manageable through manual inspection. Links connecting nodes within the same intersection are defined as internal links, as visible in **Figure 4**.

In the U.S., agencies that model road networks often represent some two-way roads with a centerline that allows bidirectional travel and others as a pair of unidirectional lines. The data structures developed in this research allow for this mix of input representation, though ultimately the dual graph representation requires that all bidirectional segments be converted to a pair of unidirectional segments.

Figure 4. Three intersection types in the Boston network. Left: junctions of undivided roads (intersection has a single node). Center: undivided road meets a divided road (intersection has two nodes). Right: two divided roads meet (intersection has four nodes).

5.1.3 *Legs*

An intersection leg is the unit a cyclist crosses. Unless a median exceeds 100 ft (30 m), cyclists typically cross both directions of a road in a single pass, regardless of carriageway representation. A leg therefore corresponds to one external link for centerline roads and a pair for divided carriageways.

Legs are formed by sorting external incident links by compass bearing counterclockwise from north, then merging adjacent links belonging to the same divided road and street name into a single leg. Legs are indexed from 0 by bearing, counterclockwise from north.

5.1.4 *Crossings*

A crossing represents traversal of one intersection leg, from an approach link to a departure link. It is modeled as a relation between an intersection, an approach link, a departure link, and the crossed leg — both approach and departure links must be external with appropriate directionality. There is a one-to-one correspondence between legs and crossings at any intersection.

Crossings need no geometry for routing, but for visualization, each is represented as a short line segment offset from the intersection centroid (**Figure 5**). At T-intersections, crossings that occur only as part of a left turn appear as diagonal segments. Each crossing record stores: intersection ID, from-leg and to-leg indices, crossed-leg ID, stop sign presence, RRFB presence, island depth, crossing length, and xLTS.

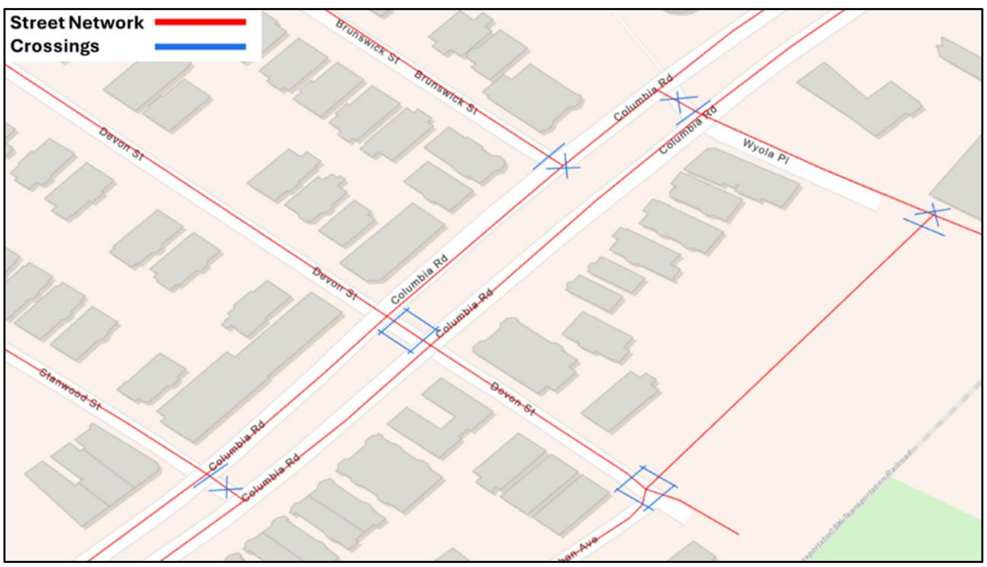


Figure 5. Non-routable crossing features (blue) and street network (red)

5.1.5 *Movements*

A movement relates an approach link, a departure link, and an intersection, both links external with appropriate directionality. It consists of the crossings corresponding to legs between the approach and departure, proceeding counterclockwise. For a movement from leg i to leg j at an n-leg intersection, the crossed legs are indexed i through $j\text{-}1 \ (mod\ n)$. mLTS is the maximum xLTS of crossed legs, or 1 if none are crossed **Equation (1)**.

Each directed road segment becomes a dual node, representing the downstream end of its segment. Bidirectional links produce two dual nodes; one-way segments produce one. No dual nodes are created for internal links.

5.1.6 Dual Nodes and Edges

At each intersection, a dual edge is created for every movement between an approaching and departing segment, excluding U-turns. **Figure 6** illustrates the resulting layout for a crossroads. Turn restrictions based on directionality are handled implicitly since movements violating approach or departure directionality are never generated.

Dual edge length equals the destination link length plus internal link lengths traversed at the intersection. Each dual edge carries two stress attributes: mLTS of the movement and sLTS of the destination segment, consistent with dual nodes representing segment downstream ends. Turn penalties can optionally be assigned as incremental lengths — a 20-second left-turn penalty at 4.5 m/s corresponds to 90 m of incremental length.

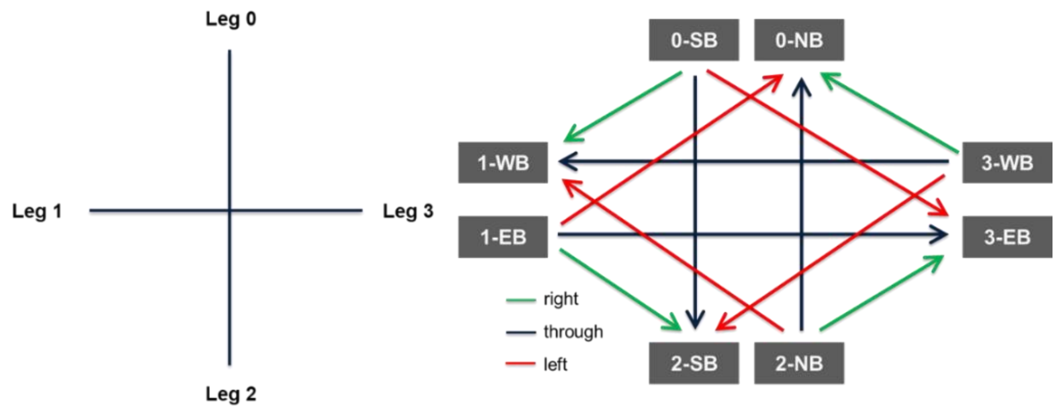


Figure 6. Dual graph node and edge layout for a four-leg intersection.

5.2 Routing on the Dual Graph

5.2.1 Graph Construction

Dual nodes are created for every external link and dual edges for every legal movement at every intersection. Dual nodes carry no cost; edges carry a length plus an optional turn penalty as incremental length, together forming their cost. Each dual edge also carries mLTS and segment level of traffic stress (sLTS) attributes.

5.2.2 LTS-Constrained Routing

For a given stress threshold k, dual edges with mLTS > k or sLTS > k are filtered out before routing. Dijkstra's algorithm is then run on the filtered graph, ensuring no path traverses a segment or crossing above the threshold, consistent with the weakest-link principle.

Round-Trip Distance and Detour

Because of one-way streets and asymmetric infrastructure, connectivity requires that a cyclist can both reach a destination and return by a low-stress route. Return paths are obtained efficiently by running Dijkstra on the edge-reversed graph from the same origin. Distance between an OD pair is defined as half the round-trip distance.

5.2.3 Round-Trip Distance and Detour

The LTS framework also limits detour, since a low-stress route involving excessive detour would not realistically be used. Rather than a hard cap, we use a gradual propensity function as in Furth et al. (2018). For a given OD pair at stress level *k*, let L_k denote the low-stress distance and lun the unconstrained distance. Relative detour propensity is based on the ratio L_k/L_{un}, with full propensity up to 1.20 declining linearly to zero at 1.50 (**Equation (2)**, **Figure 7** left panel). These thresholds are consistent with Broach et al. (2012), who found cyclists accept average relative detours of 16 to 26 percent for lower-stress routes.

$$\pi_{rel} = \begin{cases} 1, & if\ L_k/L_{un} \leq 1.20 \\ \dfrac{1.50 - L_k/L_{un}}{0.30}, & if\ 1.20 < L_k/L_{un} < 1.50 \\ 0, & if\ L_k/L_{un} \geq 1.50 \end{cases} \quad \textbf{(2)}$$

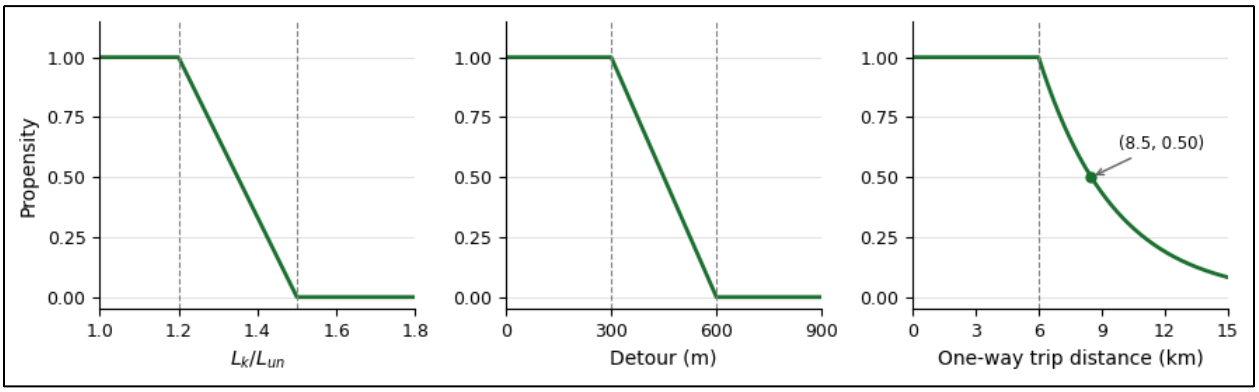


Figure 7. Components of the propensity function. Left: relative-detour propensity, based on the ratio of low-stress distance to unconstrained distance. Center: absolute-detour propensity, which overrides when it is greater than relative detour propensity. Right: distance component, based on one-way low-stress trip distance.

For short trips, detour propensity is based on absolute detour, with full propensity up to 300 m declining linearly to zero at 600 m (**Equation (3)**, **Figure 7** center panel).

$$\pi_{abs} = \begin{cases} 1, & if\ detour \leq 300\ m \\ \dfrac{600 - detour}{300}, & if\ 300 < detour < 600 \\ 0, & if\ detour \geq 600\ m \end{cases} \quad \textbf{(3)}$$

The greater of the two detour propensities applies for any given trip, making absolute detour the binding constraint for shorter trips and relative detour for longer ones:

$$\pi_{detour} = \max(\pi_{rel}, \pi_{abs}) \quad \textbf{(4)}$$

A distance propensity component π_{dist} accounts for people's limited willingness to cycle long distances (Furth et al., 2018). To avoid hard-cutoff boundary effects, π_{dist} decays exponentially beyond 6 km, halving every 2.5 km (**Equation (5)**, **Figure 7** right panel).

$$\pi_{dist} = \begin{cases} 1, & if\ L_k \leq 6{,}000\ m \\ e^{-\alpha(L_k - 6{,}000)}, & if\ L_k > 6{,}000\ m \end{cases} \quad (5)$$

$$\text{where } \alpha = \frac{\ln(2)}{2{,}500} \approx 0.000277\ m^{-1}$$

Final propensity for any OD pair is the product of the detour and distance propensities:

$$\pi = \pi_{detour} \cdot \pi_{dist} \quad (6)$$

Therefore, both detour and distance must be reasonably high for a trip to receive high propensity. **Figure 8** shows the resulting propensity surface as a function of low-stress distance and absolute detour. In accessibility analysis, each OD pair's demand is weighted by its propensity.

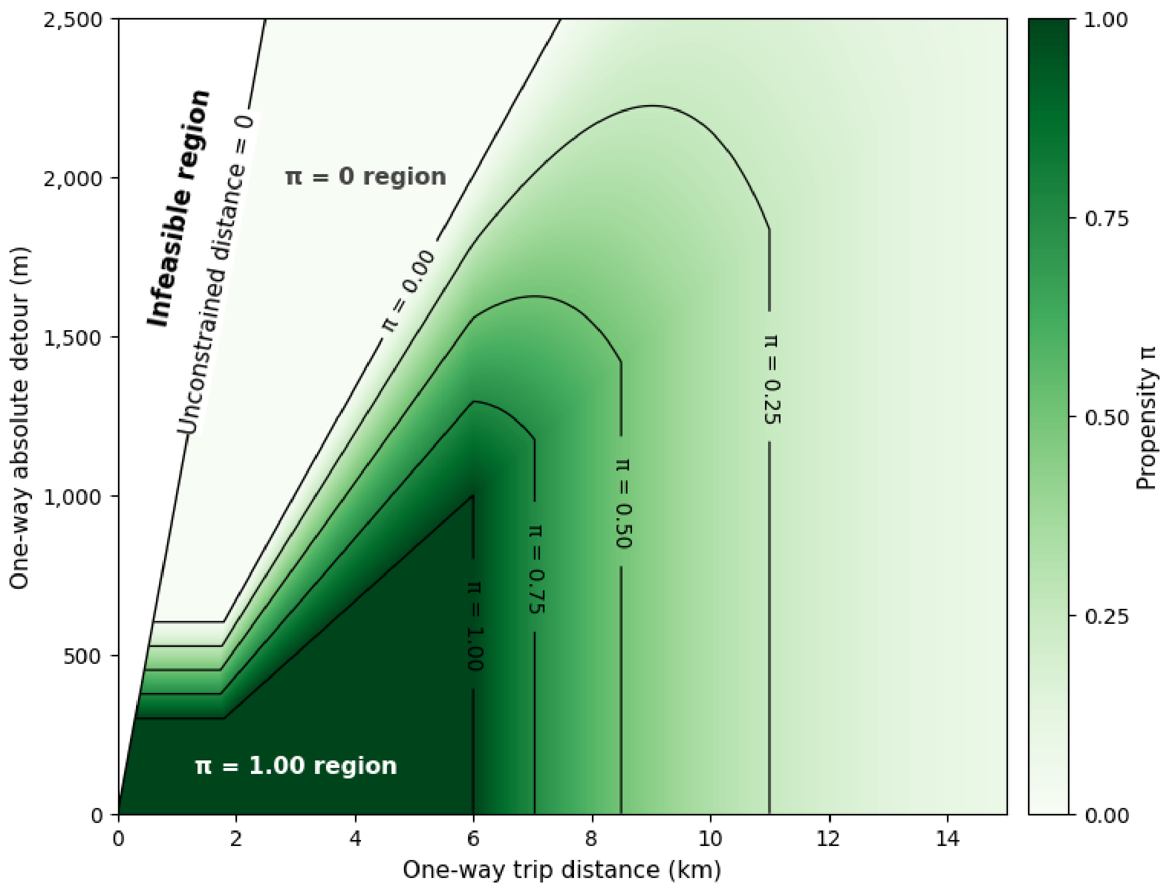


Figure 8. Propensity surface as a function of one-way low-stress trip distance and one-way absolute detour, with contours at selected values of π.

6. CASE STUDIES

6.1 Study Areas

Methods were applied in Montreal (population 2 million) and the Boston area (Boston, Brookline, Cambridge, Somerville; ~940,000). Montreal analysis was limited to identifying critical crossings; Boston served as the basis for jobs accessibility analysis.

6.2 Data Sources and Integration

6.2.1 Montreal

The base network merged streets and cycling infrastructure into a unified routing layer. Speed data came from Intact Insurance Company; ADT was estimated via regression against city traffic counts. Segment LTS was computed for the full network (Sadeghinasr, 2023); all data from 2021. xLTS required additional sources: signal and stop locations from city GIS, crossing lengths from network geometry, crossing islands inferred from divided-road coding, right-turn volumes from the city's travel demand model, and bike signal and box locations from city GIS. Freeway ramp junctions and one blind entry hazard were entered manually in consultation with city staff.

6.2.2 Boston Area

The base network came from MassDOT's road network file, which had undergone substantial manual correction in a prior study (Putta and Furth, 2021), including one-way street directions, lane counts on one-way and divided streets, and divided road identification. Centerline presence was checked in Google Maps and entered manually, as it affects stress on some streets. Bicycle infrastructure data came from the MassDOT Bike Layer and City of Boston (late 2025), supplemented by manual collection of bike lane width, reach, and parking adjacency. Speed and ADT for arterials and collectors came from StreetLight Data provided by the City of Boston.

6.2.3 Accessibility Measures

Jobs accessibility for each segment is the propensity-weighted sum of jobs reachable by low-stress round trip. Because dual nodes represent segment downstream ends, origin segment LTS does not affect accessibility — cyclists effectively walk to the end of their block before riding. To avoid the symmetric problem on the destination side, the shortest path tree was extended by one dual edge from every reached node, allowing cyclists to walk the final partial segment to their destination.

7. RESULTS

7.1 Crossing Stress Distribution

Table 6 shows the xLTS distribution for all crossings in Montreal and Boston. In both cities, nearly 90% of crossings rated xLTS 1 and only 2–3% were high-stress (xLTS 3–4). As both cities are walkable and transit-oriented by North American standards, high-stress crossings may be more prevalent elsewhere.

Table 6. Distribution of crossings by xLTS level

xLTS	Montreal	Boston Area
1	64,476 (89.3%)	36,717 (89.4%)
2	6,211 (8.6%)	3,177 (7.7%)
3	1,257 (1.8%)	757 (1.9%)
4	231 (0.3%)	424 (1.0%)
Total	72,175	41,075

7.2 Critical Crossings

A crossing is critical if its xLTS exceeds the LTS of both its approach and departure segments. Montreal had 814 critical crossings and the Boston area 1,199; **Table** 7 breaks these down by xLTS level and approach/departure LTS.

Table 7. Critical crossings by xLTS level and approach/departure segment LTS

xLTS	Approach & Departure LTS ≤	Montreal	Boston Area
2	1	367	716
3	1	31	180
3	2	317	127
4	1	1	75
4	2	41	32
4	3	84	69
Total		814	1,199

Figure 9 and Figure 10 map critical crossings in Montreal and Boston where approach and departure segments have LTS ≤ 1, making them barriers invisible to segment-only analysis. The most common cases are unsignalized crossings of busy arterials and signalized intersections with heavy right-turn traffic on roads with low-stress bike lanes. Critical crossings cluster along major arterials in both cities, with long uninterrupted runs creating significant barriers that force considerable detour to cross from one side to the other.

Figure 11 illustrates the impact of critical crossings on school accessibility. The LTS 1 catchment of Brooke High School in Mattapan shrinks substantially when crossing stress is enforced: a southern neighborhood accessible by segment LTS alone (black) becomes unreachable (green). The critical crossing is an unsignalized crossing of Cummins Highway, a road that is low-stress to ride along due to protected bike lanes but stressful to cross.

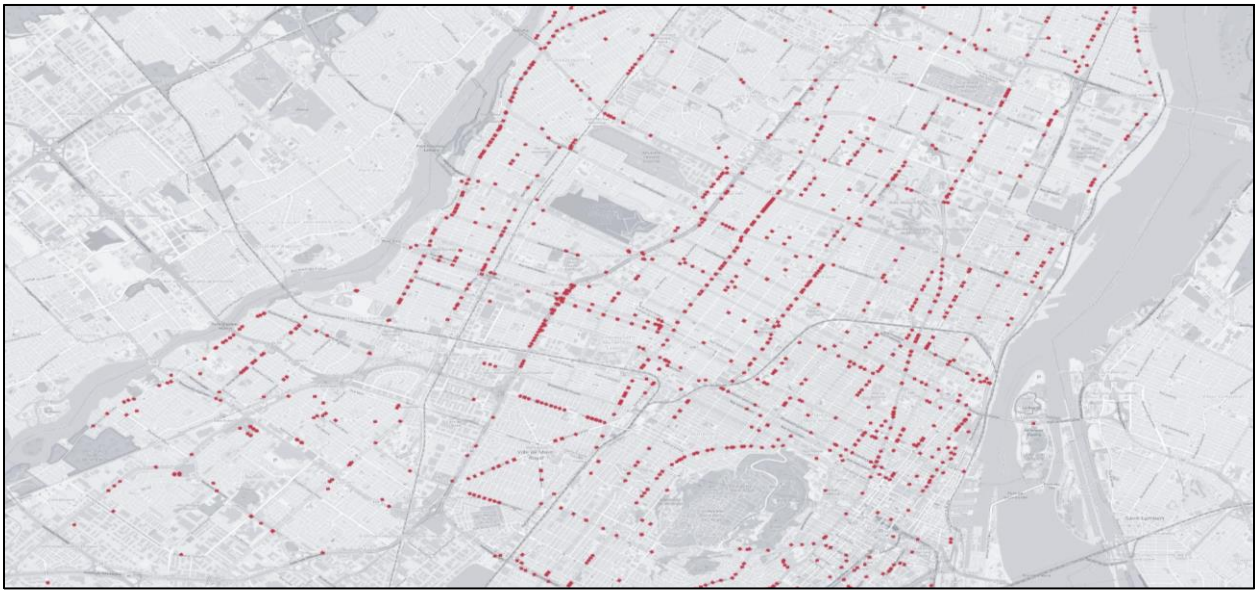


Figure 9. Critical crossings on the low-stress network (segment LTS ≤ 2) in Montreal.

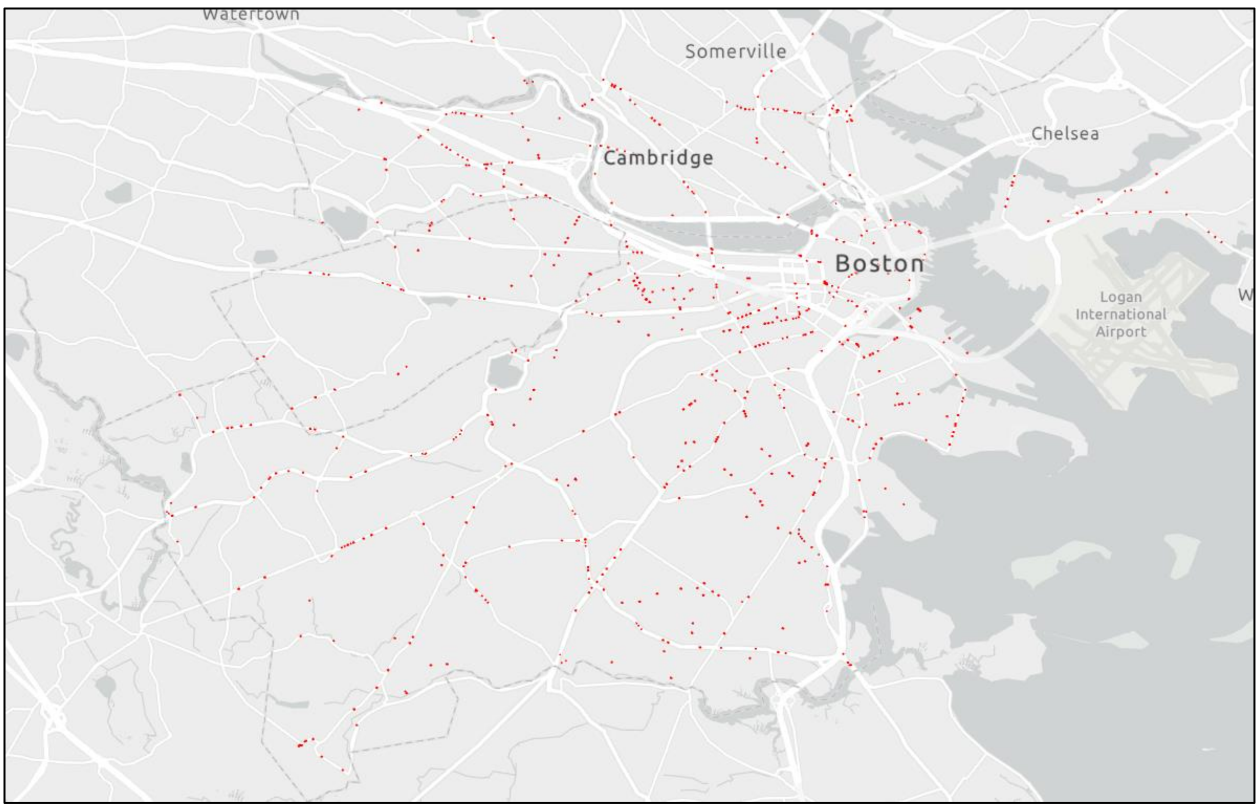


Figure 10. Critical crossings on the low-stress network (segment LTS ≤ 2) in the Boston area.

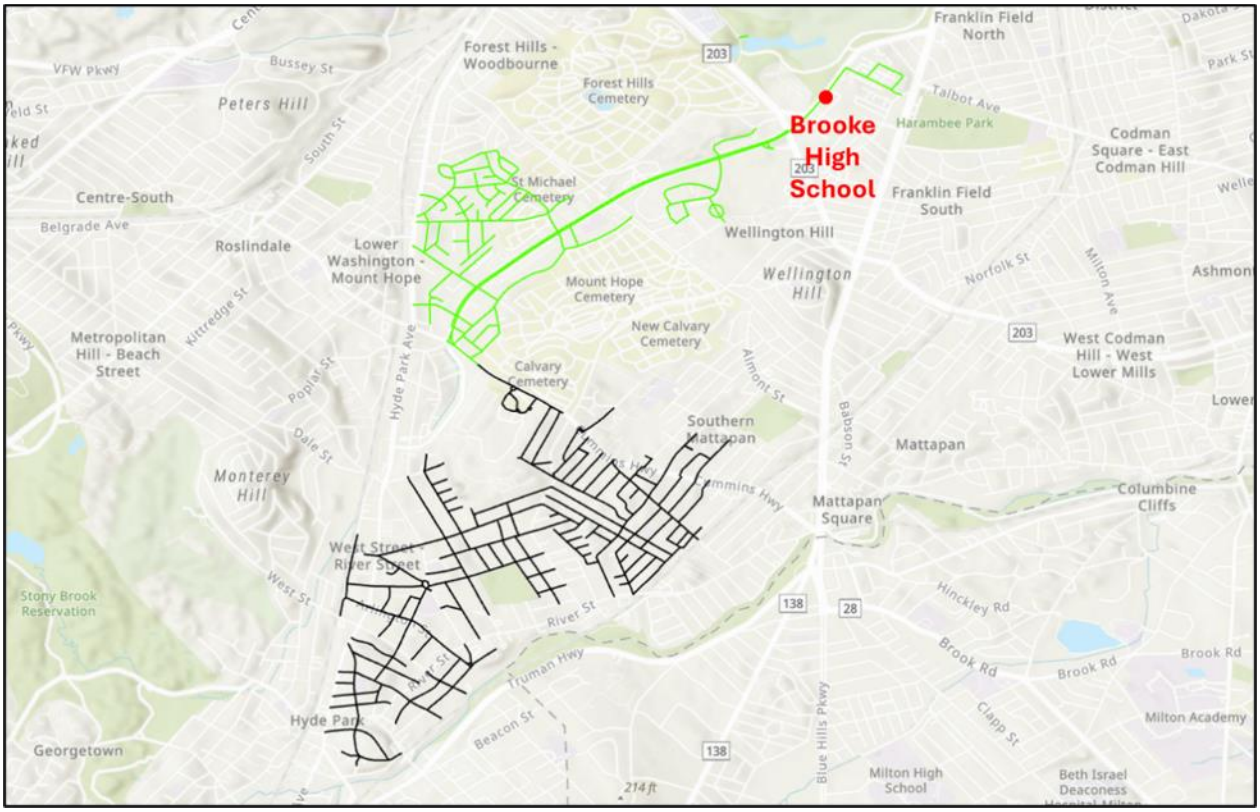


Figure 11. LTS 1 cycling catchment of Brooke High School ignoring xLTS (black and green) and accounting for xLTS (green only). The difference is due to a critical crossing of Cummins Highway.

7.3 Accessibility to Jobs in the Boston Area

Origin-based jobs accessibility A_i is the propensity-weighted sum of jobs reachable from segment i at a specified stress level (**Equation (7)**). Average accessibility for a subarea is the population-weighted mean across origin segments (**Equation (8)**), where P_i is population at segment i, E_j is jobs at destination j, and π_{ij} is trip propensity.

$$A_i = \sum_j E_j \times \pi_{ij} \tag{7}$$

$$\bar{A}^{jobs} = \frac{\sum_i (P_i \times A_i)}{\sum_i P_i} \tag{8}$$

Table 8 shows average jobs accessibility as a percentage of total jobs (~1 million). With xLTS enforced, residents reach 0.2% of jobs at LTS 1 and 10.9% at LTS 2. Enforcing xLTS reduces LTS 1 accessibility by more than 75%, indicating intersections are a major barrier to children's mobility. Even at LTS 4, accessibility falls short of 100% due to distance propensity.

Table 8. City-wide bike accessibility to jobs in the Boston area by LTS, with and without crossing stress enforced

Stress limit	xLTS not enforced	xLTS enforced
LTS 1	9,056 (0.9%)	2,339 (0.2%)
LTS 2	116,036 (12.1%)	103,892 (10.9%)
LTS 3	515,543 (51.4%)	511,517 (51.0%)
LTS 4	575,152 (57.4%)	575,152 (57.4%)

Figure 12 and Figure 13 map origin-based jobs accessibility at LTS 1 and LTS 2.

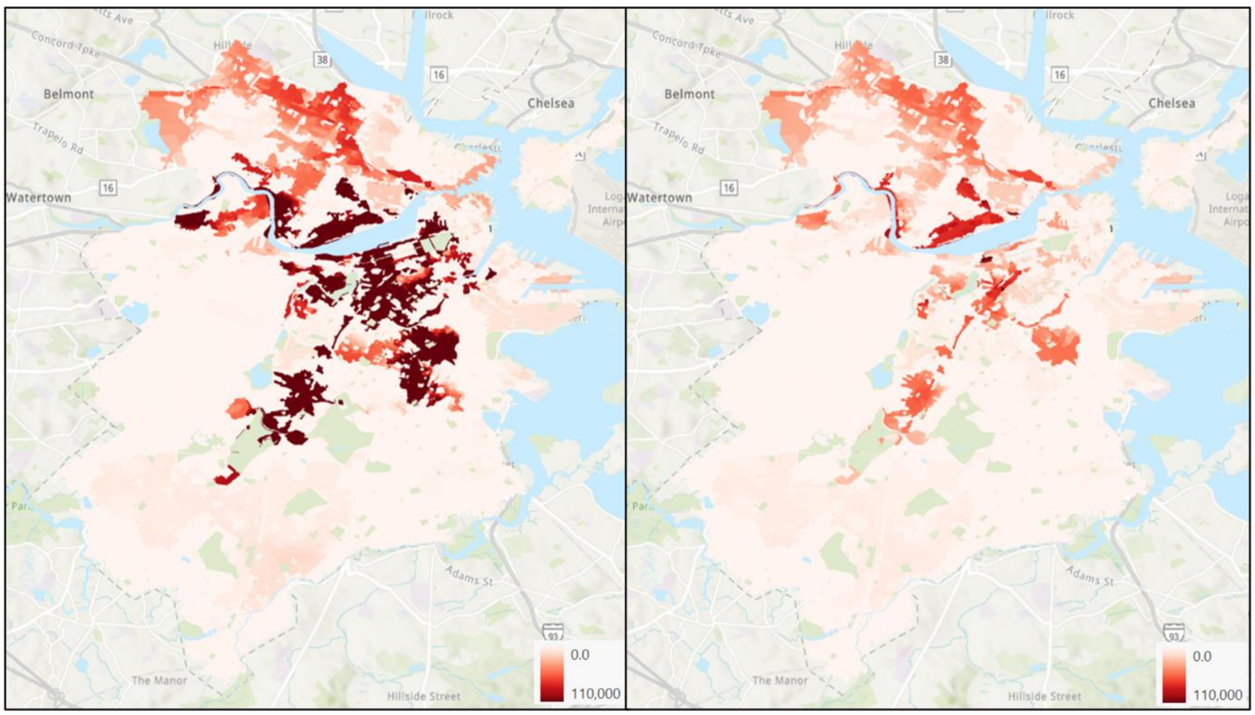


Figure 12. Origin-based jobs accessibility at LTS 1, ignoring xLTS (left) versus accounting for xLTS (right)

Table 9 summarizes results by area. At LTS 2 with xLTS enforced, Cambridge and Somerville residents can reach about 20% of study area jobs, versus 9% for Boston and 2% for Brookline. Within Boston, accessibility is strongest in the central district and closer-in neighborhoods, and falls to 2% or less in southern districts such as Dorchester, Mattapan, Hyde Park, and West Roxbury. The impact of crossing stress is strong everywhere at LTS 1 and milder at LTS 2, with South Boston showing the largest LTS 2 impact: jobs accessibility drops from 17% to 11% when crossing stress is enforced, suggesting a few strategic crossing improvements could substantially improve connectivity there.

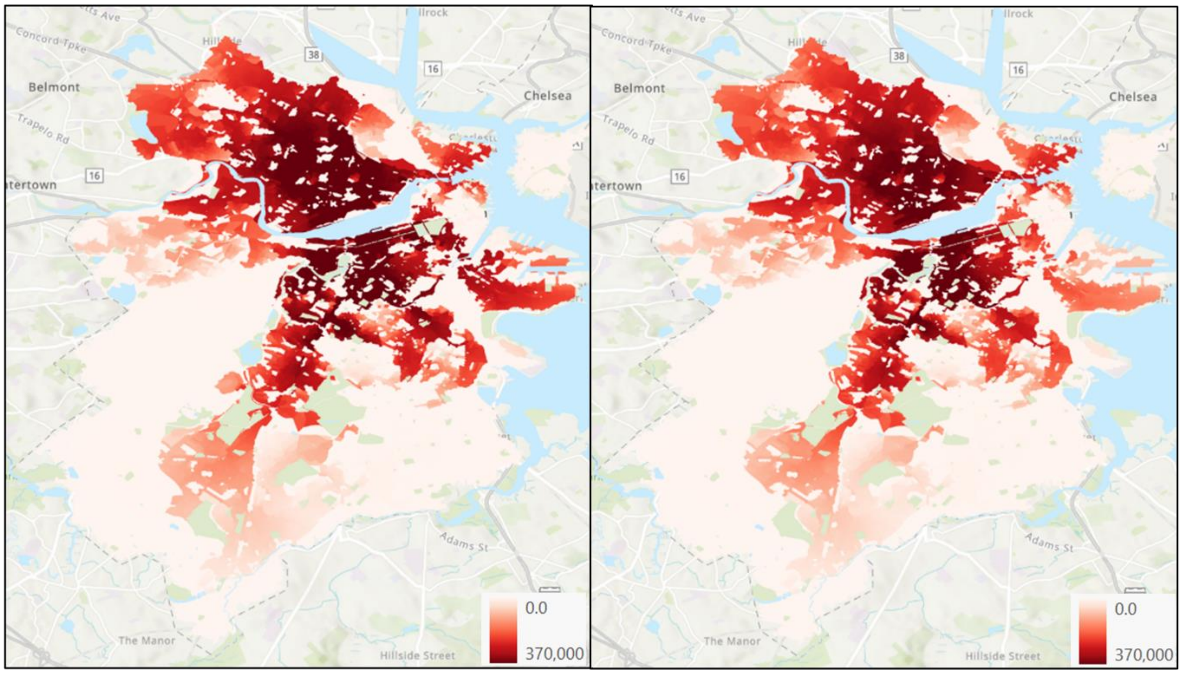


Figure 13. Origin-based jobs accessibility at LTS ≤ 2, ignoring xLTS (left) versus accounting for xLTS (right)

Table 9. Percent of jobs accessible with and without crossing stress enforced

Home District	Population	LTS 1		LTS 2	
		xLTS not enforced	xLTS enforced	xLTS not enforced	xLTS enforced
Boston - Central	174,840	2.4%	0.3%	19.2%	16.8%
Boston - Dorchester	149,626	0.2%	0.0%	2.7%	2.3%
Boston – Allston/Brighton	83,022	0.3%	0.1%	7.4%	6.9%
Boston - Roxbury	67,141	1.6%	0.2%	12.4%	11.2%
Boston - Jamaica Plain	50,536	1.7%	0.4%	14.4%	13.6%
Boston - South Boston	39,182	0.3%	0.2%	16.5%	10.6%
Boston - West Roxbury	34,943	0.1%	0.1%	0.4%	0.4%
Boston - Hyde Park	34,430	0.1%	0.1%	2.2%	2.1%
Boston - Roslindale	33,611	0.2%	0.1%	8.3%	7.7%
Boston - Mattapan	26,780	0.0%	0.0%	1.1%	1.1%
Boston - Charlestown	21,355	0.1%	0.1%	13.1%	12.6%
Boston Total	**715,466**	**1.0%**	**0.2%**	**10.1%**	**8.9%**
Brookline	68,445	0.0%	0.0%	2.1%	1.9%
Cambridge	137,040	1.3%	0.4%	21.9%	20.2%
Somerville	96,793	1.0%	0.7%	20.1%	18.7%
Metro Total	**1,017,744**	**0.9%**	**0.2%**	**12.1%**	**10.9%**

8. CONCLUSIONS

Intersections have long been recognized as barriers to low-stress cycling, but until now no method existed to incorporate that barrier effect into bike network evaluation. This study addresses that gap with two major contributions: xLTS criteria for quantifying crossing stress, and a dual graph network model for enforcing those criteria in routing and accessibility analysis.

The xLTS criteria are practical yet ambitious. Most require little beyond what segment-level LTS analysis already needs; turning movement volumes, required for one criterion, were available in Montreal but not Boston. While the criteria have not been econometrically validated, they are grounded in bicycle safety research and planner experience, and were reviewed by local planners in both cities. For unsignalized crossings, gap acceptance theory provides a principled way to combine lanes, volume, speed, crossing islands, and cyclist type into a consistent crossing stress rating.

Case studies showed that high-stress crossings are a minority but that critical crossings — where xLTS exceeds the LTS of both approach and departure segments — are numerous enough to constitute real barriers. In Boston, enforcing crossing stress reduced LTS 1 jobs accessibility by more than 75%, confirming that intersections are a major barrier to children's mobility. At LTS 2, the reduction was a modest 7%, which may reflect Boston's pedestrian-oriented character and relatively few multilane roads. A more auto-oriented city would likely show a stronger barrier effect at LTS 2.

Future research needs include empirical validation of the xLTS criteria and testing the value of turn penalties, which the dual graph framework now makes possible.

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