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Evaluating Design Solutions for Cycle Tracks along Urban Arterial Roads: Case Study in Toronto

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Abstract: Many arterial roadways in the City of Toronto justifiably focus on motor vehicle traffic, but unfortunately they are not very accommodating to cycling. The City has identified the need for a dedicated bicycle facility along University Avenue, a major north-south arterial road in the city's downtown core. Providing a safe and comfortable route for cyclists is key to encouraging cycling as a mode of transportation. However, it must be balanced with accommodating the high volume of motor vehicles present. The purpose of this paper is twofold: (1) to present a comprehensive evaluation of two common design alternatives for bicycle facilities along University Avenue and (2) to present a detailed design of the best alternative. The study area encompasses University Avenue between Front Street West and College Street West, which is a span of approximately 1.9 km. The main alternatives include a separated one-way cycle track and a raised cycle track. Both design alternatives are open to new innovations specific to the University Avenue corridor, subject to City's design standards. The two alternatives were evaluated using a unique weighted scoring method that involved multiple criteria: safety, economic, level of service, and constructability. The results show that the best alternative is the separated one-way cycle track which was designed in detail and its level of service was evaluated using Synchro simulation software. Based on this study, some practical guidelines for bicycle facilities on major roads in urban settings are presented.

1 INTRODUCTION

The City of Toronto has identified that significant population growth is occurring in the downtown and midtown areas of Toronto. This growth warrants the expansion of the city's current bicycle network to create a safe and comfortable environment, encouraging people of all ages to cycle. The City's Vision Zero Road Safety Plan has identified an alarming number of cyclist injuries and fatalities due to the lack of adequate cycling infrastructure. In light of these safety concerns, the City has expressed the need for additional dedicated bicycle facilities. The ultimate goal of this plan is to eliminate all fatalities and serious injuries on the streets of Toronto.

The City's Midtown in Focus project has identified the need for north-south bicycle facilities to connect the Yonge-Eglinton neighbourhood to the downtown core. With the need for ongoing expansion of the cycling network, the City has released a request for proposal to reconfigure University Avenue to incorporate dedicated bicycle facilities. Keeping in mind that the safety of cyclists is a high priority for the City, innovative design solutions were developed to integrate these facilities on University Avenue. This project will allow for the City to become one step closer to achieving its long-term goal.

The original project by the City aims to provide dedicated bicycle facilities along the University Avenue/Avenue Road/Oriole Parkway corridor from Front Street West to Eglinton Avenue West. However, given the vast length of the corridor, the focus of the study was on the segment of the corridor between Front Street W. and College Street W. including considering the transition of University Avenue into Queen's Park Crescent. Refer to Section 3.3 for a more in-depth description of the proposed route. The various tasks involved in the project are depicted in Fig. 1 and involved a literature review, evaluation of existing conditions of the project area, development of two design alternatives, evaluations of the two alternatives to select the best, and a detailed design of the best alternative. The literature review included relevant topics such as safety analysis (e.g. bus-bicycle conflict areas), geometric design (e.g. signalized intersections and bike boxes), economic analysis, capacity and level of service (LOS), and a review of case studies. More details about the study presented in this paper can be found in Bandiera et al. (2019).

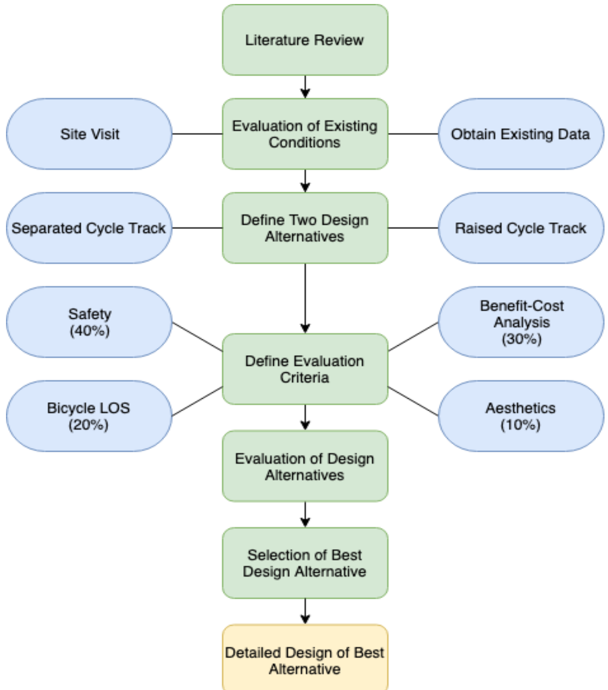


Figure 1: Logical flow of project tasks

The following sections describe the study area and the design alternatives identified. The succeeding sections describe the proposed evaluation methodology, including evaluation criteria and selection of best alternative. A detailed design of the best alternative is then presented followed by conclusions.

2 STUDY AREA AND CORRIDOR

The length of the University Avenue corridor included in the scope of work (beginning at Queen's Park Crescent and ending at Front Street W.) is approximately 1.8 km long. The segment from College Street to Richmond Street W. consists of an eight-lane roadway in both the north and south directions with a median of varying in width running along the centre. This median incorporates historical features and public spaces. The curb lane in the northbound and southbound directions is currently designated for on-street parking exclusively during off-peak hours.

South of Queen Street W., the curb lane is not currently designated for on-street parking. At Adelaide Street W. the median dissolves, changing the configuration of the roadway from four lanes to three lanes in either direction. This configuration continues along University Avenue until south of Wellington Street W., where the roadway diverges to two lanes in each direction, terminating on Front Street W. There are existing cycling facilities that either intersect with or surround University Avenue, as seen in Figure 2. After analyzing the City of Toronto's current bicycle routes, it was determined that these routes serve a high volume of cyclists. Design alternatives that integrate these existing bicycle facilities and create a more connected cycling network were identified.

The existing bicycle facilities in the vicinity of the University Avenue corridor: (1) College Street W. - one-way east-west bicycle lanes, (2) Richmond Street W. - one-way westbound cycle track on the north side, (3) Adelaide Street W. - one-way eastbound cycle track on the south side, and (4) Simcoe Street - one-way north-south cycle tracks.

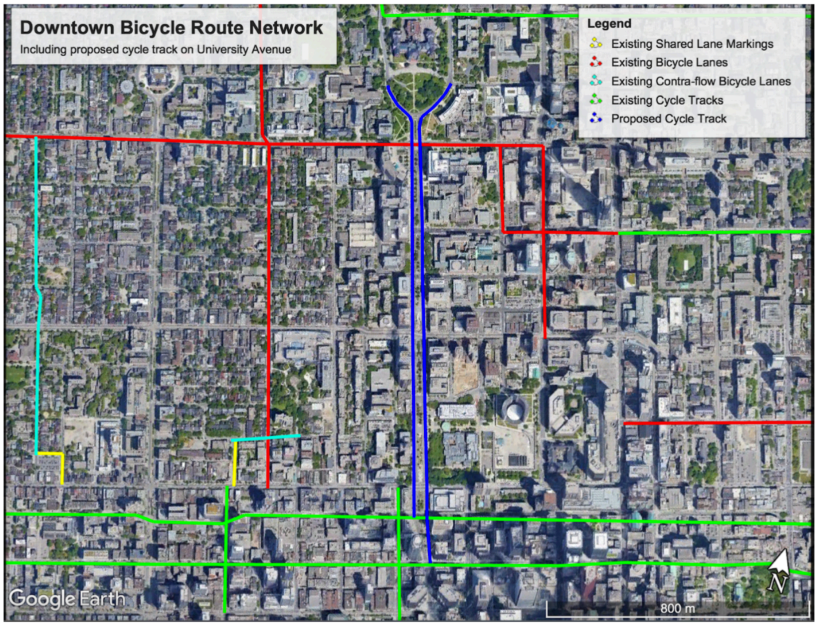


Figure 2: Map of Downtown Bicycle Network Including Proposed Route

Along University Avenue there are a number of public transportation routes. Streetcar crossings pose as a hazard for cyclists crossing intersections, due to the possibility of the tires of the bicycle getting caught in the tracks. Subway entrances pose as a unique design challenge due to the safety risks of cyclists colliding with pedestrians entering or exiting the subway. At particular locations, bus stops and bus shelters were identified as a point of conflict between cyclists and pedestrians. Passengers boarding and disembarking can interfere with cyclists as they travel past the bus stop. Due to this concern, each alternative minimizes the potential conflicts between cyclists and pedestrians.

Sidewalk widths along University Avenue vary along the corridor due to varying building setback distances. Along Queen's Park Crescent the sidewalk width is approximately 2 m, which increases to 7 m along the west side and 5 m along the east side of University Avenue. The largest sidewalk width of 8 m is located at the intersection of Armoury Street and University Avenue. The bicycle LOS of the existing corridor is E. This was calculated using a method created by the City of Gainesville, Florida. This method takes a wide variety of factors into account and is considered more in-depth than the methodology used by both the State of Florida and the Highway Capacity Manual (Dixon, 1996).

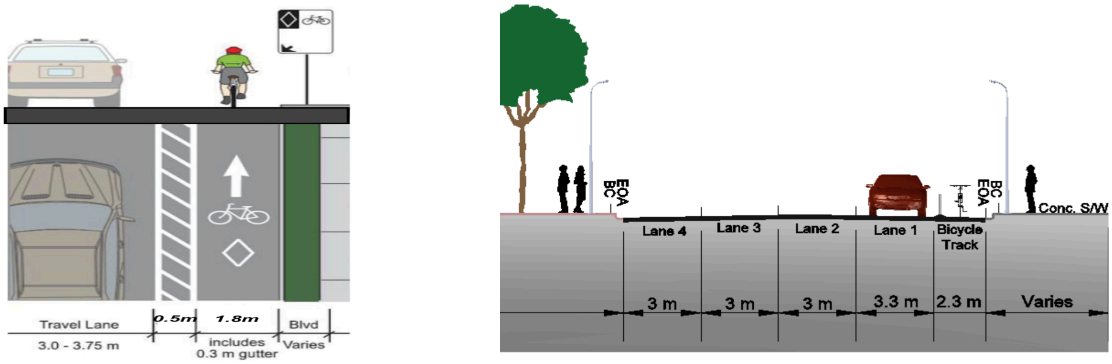
3 DESIGN ALTERNATIVES

The three alternatives originally considered were a separated one-way cycle track, a raised one-way cycle track, and a separated two-way cycle track. It would be difficult to accommodate the addition of a two-way cycle track along University Avenue unless it is situated within the center median. However, given that existing historical features and public space are present, it is not feasible. Therefore, this alternative was rejected. The remaining two alternatives were evaluated in detail.

3.1 Alternative 1: Separated One-Way Cycle Track

A separated one-way cycle track was the first of two alternatives evaluated. This facility is level with the surface of the road, however it differs from a traditional bicycle lane as it features horizontal separation between cyclists and vehicles. This separation can be in the form of a painted buffer on the surface of the roadway, or a physical barrier such as a flexible bollard, planter, or on-street parking where space permits (OTC, 2013). The barrier and coloured pavement markings allow it to be perceived by cyclists and motorists as a separate entity within the roadway.

Separated cycle tracks require little modification to the existing roadway. The central median and lane widths will require reconfiguration to accommodate the cycle track. The four existing lanes on University Avenue are 3.5 m wide, totaling 14 m in each direction. According to City of Toronto Road Engineering Design Guidelines, the minimum lane width along a 40 km per hour through lane is 3 m, and 3.3 m for curb lanes featuring bus routes. Common separated one-way cycle track configurations can be seen in Figure 3. This proposed cycle track would feature a lane width of 1.8 m and buffer width of 0.5 m.

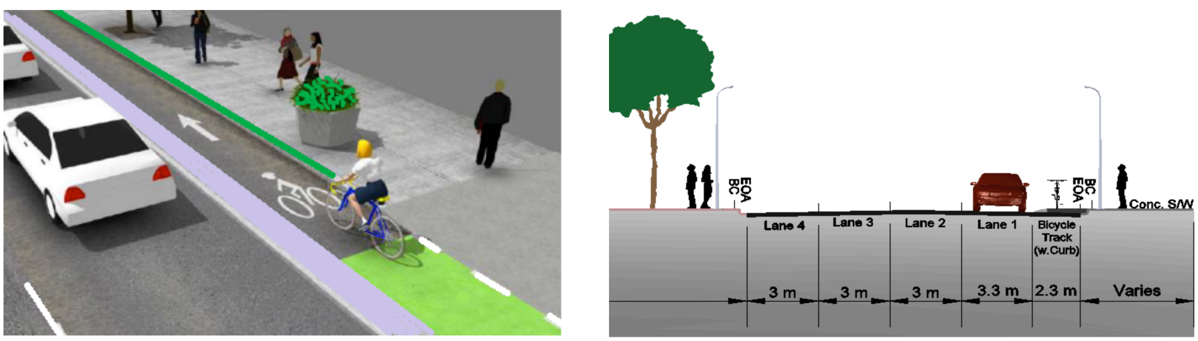


(a) Plan (b) Cross section

Figure 3 Separated Cycle Tracks with Different Buffer Types (OTC, 2013)

3.2 Alternative 2: Raised One-Way Cycle Track

A one-way raised cycle track is similar to a separated cycle track, however in place of a physical barrier, there is a difference in elevation between the roadway and the cycle track. This type of bicycle facility can be level with the sidewalk or situated at an intermediate level between road and sidewalk level. The aforementioned option would include a mountable curb between the road and the cycle track. Due to the fact that there is an elevation difference between cyclists and vehicles, the raised cycle track is seen as a desirable bicycle facility as indicated in the Peel Long Range Master Plan (Region of Peel, 2012). A typical one-way raised cycle track can be seen in Figure 4.



(a) Plan (b) Cross section

Figure 4 Raised Cycle Track with Mountable Curb (NACTO, 2018)

Of the two alternatives, the one-way raised cycle track required greater reconfiguration of the roadway. The raised cycle track is elevated from the surface of the road, providing greater separation from vehicles than a separated cycle track. The lane width of the raised cycle track must be between 1.5 m and 2.0 m. This alternative takes a similar approach to the first alternative in minimizing lanes widths. The through lanes need to be narrowed from 3.5 m to 3.0 m, and the curb lane needs to be narrowed to 3.3 m (Toronto Transportation Services, 2017). The proposed raised cycle track would feature a lane width of 1.8 m, and a mountable curb width of 0.5 m.

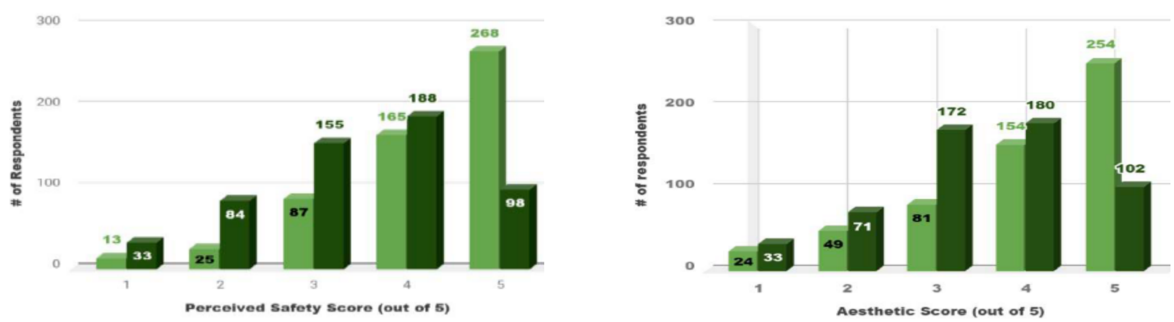
4 EVALUATION METHODOLOGY

4.1 Evaluation Criteria

4.1.1 Safety

Safety was evaluated using two categories: (1) perceived user comfort and safety and (2) percent reduction of cyclist conflicts. For perceived user comfort and safety, an overlooked aspect of safety, is the user perception of safety of a bicycle facility. Typically, users are less likely to ride a bicycle if they do not feel safe and comfortable while doing so. It is for this reason that cyclists often choose streets which have cycling infrastructure over those that do not. It has been identified that standard bicycle lanes are inadequate from the perspective of the general population; facilities which offer more separation from vehicles are thought to be more comfortable (McNeil et al., 1). To determine perceived levels of safety and comfort for users of this bicycle facility, 279 residents living within the vicinity of the City of Toronto participated in a stated-preference survey. The participants were asked to rate different cycling facilities based on how comfortable they would feel utilizing such facilities on a scale of one (meaning not at all comfortable) to five (very comfortable), similar to the aforementioned survey.

The Federal Highway Association (FHWA) definition of traffic conflict used in this study is: "A traffic conflict is an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision" (Parker and Zeeger, 1989). The traffic conflicts that could occur for cyclists were identified in three types of areas on University Avenue, based on current conditions. Seven traffic conflicts exist at signalized intersections, six exist at three-legged non-signalized intersections, and four exist on any given street stretch with no access points. These traffic conflicts for cyclists were compared to those found in the Ontario Traffic Manual (2013). A 75% reduction in traffic conflicts was considered a 'perfect' score and a 0% reduction earns a score of zero. A total of 17 cyclist-vehicle conflicts were identified. After the evaluation was completed, both alternatives scored the same, having achieved a 59% reduction in cyclist-vehicle conflicts.



(a) User Comfort and Safety (b) Aesthetics

Figure 5 Aggregate Scoring for the Two Alternatives Based on Online Survey

4.1.2 Benefit-Cost Analysis

The benefit-cost analysis considered all relevant costs and benefits, both direct and indirect. The analysis assumed a 25-year service life. Data were collected based on recent bicycle facilities constructed in Canada. The benefits were determined based on values obtained for each factor were retrieved from a benefit-cost analysis performed on bicycle lanes in Truro, Nova Scotia by Hannah E. Main in 2013. While Main's study was the primary the source for benefits, other economic papers were consulted to aid in quantifying benefits. The costs taken into consideration for the preliminary benefit-cost analysis were the construction costs and the lost revenue associated with each design alternative due to loss of parking. The construction costs include work to be done on both the east and west sides of University Avenue.

4.1.3 Bicycle LOS

The bicycle LOS was an important evaluation factor to consider. Not only does it represent the utility of the bicycle facility, it also impacts the attractiveness of cycling as a mode of transportation. The chosen method to calculate bicycle LOS was the Gainesville Mobility Plan Prototype, which expands on other more established methods used in the State of Florida Highway Capacity Manual.

4.1.4 Aesthetics

Aesthetics should be considered when designing elements of a public space such as University Avenue. To gather data, a stated-preference survey on bicycle facility aesthetics was conducted online using a Google Survey. Respondents were shown four photos; two photos of a typical design for each alternative. They were asked to score them on a scale from one (least appealing) to five (most appealing). The responses from this survey were grouped based on the alternative that the photo represents, and the responses were summed up within these groups. The aggregate results were used to create a mean score (out of 5) for each alternative. That score, "X" out of 5, was simply converted to a percent score.

4.2 Selection of Best Alternative

The proposed design alternatives were evaluated based on the four criteria and the results are shown in Table 1. Weights were assigned to the criteria as follows: safety (40%), economic (30%), bicycle LOS (20%), and aesthetics (10%). As noted, Alternative 1 scored higher in the safety, benefit-cost analysis and aesthetics categories, with an overall score of 83.7 out of 100. Conversely, Alternative 2 only scored higher in the LOS category, with an overall score of 78.3 out of 100. As such, Alternative 1 (Separated One-Way Cycle Track) was the best solution.

Table 1: Final Results of Evaluation

Evaluation Category	Evaluation Sub-Category	Alternative 1 Score	Alternative 2 Score	Maximum Available Score
Safety	Perceived Safety and User Comfort	8.32	6.24	10.00
	Percent Reduction in User Conflicts	23.40	23.40	30.00
Benefit Cost Analysis	-	30.00	25.80	30.00
Bicycle LOS	-	13.00	16.00	20.00
Aesthetics	-	7.98	6.88	10.00
Total	-	83.70	78.32	100.00

5 DETAILED DESIGN

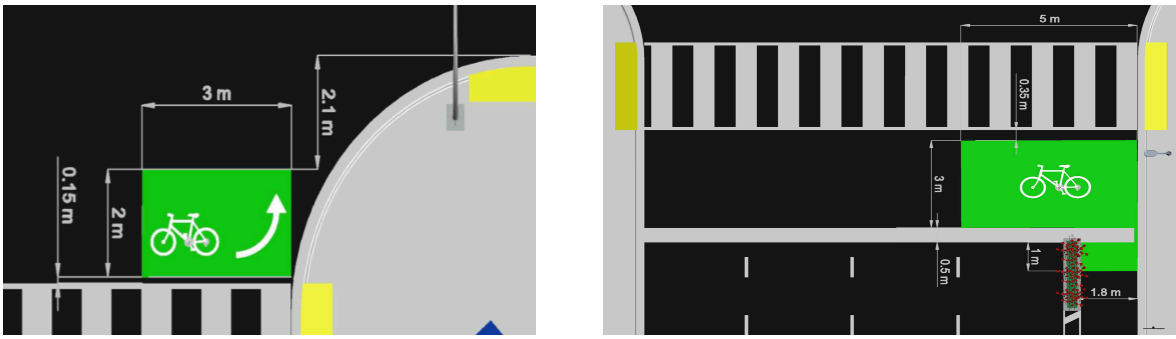
The detailed design of the best alternative was accomplished using a "Complete Street" approach in accordance with relevant design standards. Details related to intersection design, cross section design, bus stops, and Synchro simulation have been prepared as part of this project and are presented next.

5.1 Intersection Design

A critical aspect of the detailed design of the separated cycle track is the design of the intersections along University Avenue. There are both three-legged and four-legged intersections in the study area, some of which have existing cycling facilities. Adjustments to existing conditions will be required in order to improve rider safety and their integration into daily traffic. Intersection pavement markings and increased signage are the main changes that will be implemented along this corridor. The additions of bike boxes and lane markings have been explored and will be incorporated into the final design. Signs at different points in the intersection will show the location of cycle tracks and warn motorists to be aware of passing cyclists.

5.1.1 Four-Legged Signalized Intersection

Two-stage left-turn queuing boxes was the main feature implemented in four-legged signalized intersections. The areas were designed to hold cyclists between phases one and two of the turning motion. A green square is painted in the street to promote cycling facility visibility, which improves cyclist protection. The queue boxes will be 2 m wide by 3 m long. The design of this feature follows the guidance provided by the *Geometric Design Guide for Canadian Roads* (TAC, 2017). Figure 6a shows the design implemented at all four-legged signalized intersections.



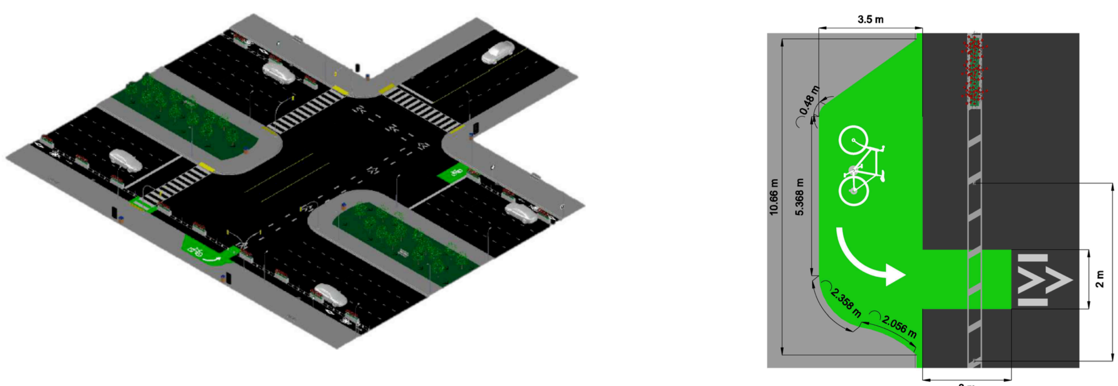
(a) Left-Turn Queuing Boxes (b) Bike Boxes

Figure 6 Dimensions and Placement of Boxes at Four-Legged Intersection

Bike boxes were also added to intersections along this corridor for cyclists moving straight or turning right through the corridor. These bike boxes are similar to the queue boxes in that they contain a green painted box in the area just before the intersection. It is added to inform motorists of cyclists in the right of way (ROW) as well as to provide a safe area for cyclists to wait while the light is not in their favour. The design of bike boxes along University Avenue has been created using a modified version of a design found in the *Ontario Traffic Manual* (OTC, 2013). The dimensions of the bike boxes will be 3 m wide by 5 m long. Figure 6b shows the placement of these bike boxes at the intersections.

5.1.2 Three-Legged Signalized Intersection

Jug-handle styled queuing boxes will be added at the three-legged signalized intersections in the study area. Guidance for the design of these features was found in the *Geometric Design Guide for Canadian Roads* (TAC, 2017). Figure 7 shows the design implemented. It is important to note that sufficient sidewalk space is required for these features to be implemented. In this situation, the sidewalks on University Avenue are wide enough to allow for both the jug-handle queuing box and the minimum sidewalk width.



(a) Full Intersection Plan (b) Jug-Handle Queue Box

Figure 7 Design of Three-Leg Intersections

5.2 Road Cross-Section Design

The proposed cross-section including the cycle tracks are shown in Fig. 8. The four existing lanes on University Avenue are 3.5 m wide, resulting in a ROW of 14 m in each direction. It was decided that the current ROW must be widened to accommodate the addition of a new cycle track within the roadway. According to City of Toronto's *Road Engineering Design Guidelines* TTS (2017)*,* the minimum lane width along a through lane with a speed of 40 km/h is 3 m, and 3.3 m for curb lanes featuring bus routes. These widths will be utilized in the reconfiguration. The proposed cycle track will feature a lane width of 1.8 m and a buffer width of 0.5 m. With the proposed changes, the overall ROW will increase to 14.6 m. The additional 0.6 m will be obtained by encroaching into median side of the roadway. A combination of planter boxes and flexible bollards will be used within the buffer area. The planter boxes have dimensions of 2.5 m in length by 0.5 m in width by 0.75 m in height, and are spaced every 5 m. The flexible bollards are 1 m in height and are centered between planter boxes.

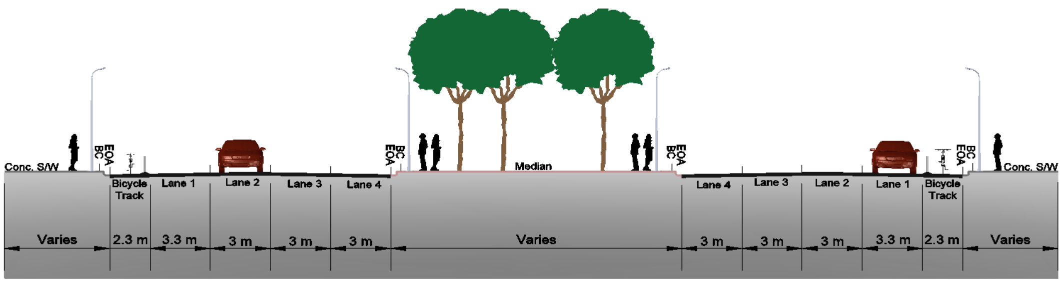


Figure 8 Detailed Cross Section of Separated One-Way Cycle Track

5.3 Bus Stops

One point of interest is the protocol for bus stops along the University Avenue corridor. Bus bump-outs will be implemented at areas where a bus stop is present. A bus bump-out is a portion of a cycle track which raises from road level to either an intermediate level or to curb level. Tactile plates are then placed around the perimeter of the elevated area, to warn pedestrians and bus passengers of the possibility of cyclists entering the area. Although the pedestrian-cyclist conflict still exists, the conflict between cyclists and buses (which is often fatal) is eliminated. This area of the road will require additional paving in order to elevate the cycle track surface to the height of the sidewalk. Signage will be added ahead of the elevated cycling areas to warn cyclists to yield to buses along the corridor. The *Geometric Design Guide for Canadian Roads* (TAC, 2017) was used as guidance when designing the bus bumpouts used. A sample bus bump-out can be found in Figure 10 following these dimensions.

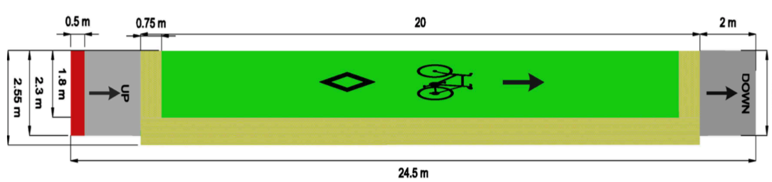


Figure 9 Design of Bus Bump-Out

5.4 Synchro Simulation

A model of University Avenue was developed using Synchro V.8 traffic analysis software to determine the effects that the new cycle track will have on the intersection LOS and intersection delay.

5.4.1 Establishing Network and Simulation Parameters

The network created had 8 nodes and included every signalized intersection between College Street W. and Adelaide Street W. It was decided to only include these nodes as this is the area in which the road is being reconfigured. The City of Toronto's *Guidelines for Using Synchro 9* (2016) was consulted during the creation of the network and during the input of data. It should be noted that the software uses the methodology from HCM 2010. Traffic counts and signal timings for these intersections were provided by the industry advisors. All traffic counts were converted to an equivalent base year of 2019 using the population growth rate from the 2016 census (Statistics Canada, 2017). All simulations were performed during the morning rush hour; this is due to the fact that, for most of the intersections, the morning rush hour traffic volumes were greater than those of the afternoon rush hour. Lane widths and storage lane lengths for the base conditions were determined via field measurements. Table 2 shows other key parameters used in creating the network and simulation.

Table 2: Network-Wide Parameters for Traffic Simulation

Variable	Value
Saturation Flow Rate*	1900 pc/h/ln
Peak Hourly Factor*	0.90
Simulation Duration*	60 min
Simulation Seed Time	7:50 AM
Simulation Recording Time	8:00 AM

* Value was specified in Toronto's *Guidelines for Using Synchro 9*

Finally, several assumptions were made due to the fact that the analysis occurred during rush hour. For all intersections where left turns are prohibited during rush hour, the leftmost lane was treated as a through lane instead of a through/left turn lane. Also, on-street parking was omitted since it is prohibited during the hour that the analysis takes place.

5.4.2 Interpretation of Results

It is important to note that in all models, many of the critical approaches are in the eastbound or westbound directions, which are not directly affected by the reconfiguration of University Avenue. Table 3 displays the simulation results for the reconfigured road using the base year of 2019. The lane widths were all reduced from the existing widths to the proposed widths (3.3 m for the curb lane, and 3 m for all other lanes). The only intersection that exhibited a decrease in LOS was Armoury Street, which decreased from A to B. The mean increase to intersection delay for all intersections was 1.8 seconds. Overall, the changes introduced in the base year do not have a profound effect on the traffic flow.

Table 3: Traffic Simulation Results for Base Year (2019) With Proposed Cycle Track

Intersection	LOS	Intersection Delay (s)	Difference vs. base model	Critical v/c ratio	Difference vs. base model	Critical Approach (LOS)
College	C	22.4	(+0.6)	0.75	(0.04)	Southbound (C)
Gerrard	B	11.5	(+0.7)	0.81	(no change)	Westbound (D)
Elm	F	118.5	(+1.6)	2.47	(no change)	Westbound (F)
Dundas	F	127.9	(+6.9)	1.98	(no change)	Eastbound (F)
Armoury	B	10.2	(+0.4)	0.69	(+0.04)	Southbound (A)
Queen	C	24.1	(+0.1)	0.72	(+0.04)	Southbound (C)
Richmond	A	8.2	(no change)	0.28	(no change)	Westbound (B)
Adelaide	D	42.0	(+4.0)	1.06	(+0.06)	Southbound (D)

5.4.3 Limitations of Results

There are several limitations that may have affected the results of the simulation. One such limitation is that the version of Synchro used does not allow for bicycle facilities to be added, and thus won't accurately depict the interaction between cyclists and vehicles. Other minor limitations of Synchro are related to non-simulation of streetcars and bus bump-outs, and the assumption that traffic growth rate equals the population growth rate.

CONCLUSIONS

With the significant population growth in downtown and midtown Toronto, it is necessary that the Toronto cycling network expand. It is also vital that the City of Toronto *Vision Zero Plan* and the *Complete Streets Guidelines* are followed for any future cycling facilities. Through the identification and evaluation of various design alternatives, a separated one-way cycle track along University Avenue, from Front Street West to College Street West, was found to provide a safe and comfortable environment for cyclists of all ages and skill levels. The detailed design of the cycle track presented in this paper uses design principles from MTO, TAC, and NACTO, which can be adapted and implemented in other urban arterial roads. The project will come at a cost to the city of approximately $4.9 Million, over two-thirds of which is from lost parking revenue. However, given the benefits to the public, it is certainly advisable for the City to invest in projects such as this. Finally, it should be mentioned that due to the vast scope of the project, several elements have been excluded, such as relocating utilities and optimizing signal timings.

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