Transportation Association of Canada

Safety Performance of Bicycle Infrastructure in Canada

November 2020

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<tr><td colspan="2">Abstract

The increasing popularity of bicycling as a mode of travel in Canada is leading many jurisdictions to develop new bicycle infrastructure that better meets the safety and mobility needs of bicyclists. However, there is an overall lack of understanding regarding the safety performance of different types of bicycle facilities in the Canadian context. This study characterizes the safety performance of various bicycle infrastructure facilities to help Canadian practitioners evaluate the potential safety performance of new bicycle infrastructure.

The report, which is designed as a resource document, is based on a comprehensive literature review, a jurisdictional survey, a series of local and international case studies, and an end user survey. In addition, the document contains a facility selection flowchart that can help practitioners to better inform the selection of a suitable bicycle facility by raising issues to consider in the selection of bicycle facilities and intersection treatments.

A key finding of the study is that there are extensive data and knowledge gaps associated with the safety performance of bicycle infrastructure in Canada. These gaps are related to collision and other surrogate safety data, bicycle and pedestrian volume data (exposure data), vehicular traffic volumes by vehicle type, information about the performance of bicycle facilities in winter conditions, and other subjects. There are also significant knowledge gaps regarding the thresholds associated with better safety performance for different factors that impact bicycle infrastructure safety in Canada (e.g. vehicular volume, bicycle volume, proportion of trucks and buses, and frequency of access points). This lack of knowledge was also found to exist beyond Canada.</td><td>Keywords

• Bicycle safety
• Bicycle infrastructure
• Bicycle lanes
• Intersection treatments
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Executive summary

The increasing popularity of bicycling as a mode of travel in Canada has resulted in the extensive development of new bicycle infrastructure in many Canadian jurisdictions. A primary goal of bicycle infrastructure is to encourage bicycling to improve public health in a safe and equitable manner, while improving the efficiency of the transportation network inclusive of all modes.

Many of the safety evaluations of existing bicycle infrastructure (comprising both facilities along road segments and intersection treatments) documented in the literature have been focused on U.S. or other international locations that may or may not be applicable to Canada. It is important to understand the factual safety performance associated with different types of bicycle facilities and bicycle intersection treatments in the Canadian context, so that more informed decisions can be made by Canadian practitioners regarding the types of facilities and treatments to implement for different locations.

This report characterizes the safety performance of various bicycle infrastructure facilities to help Canadian practitioners with more informed decision-making during facility selection. It is based on a comprehensive review of literature, a jurisdictional survey, a series of local and international case studies, and an end user survey. The document also contains a facility selection flowchart that can help practitioners better inform the choice of a suitable bicycle facility by raising safety-related issues to consider in the selection of bicycle facilities and intersection treatments.

A key finding of this project is that there are extensive data and knowledge gaps associated with the safety performance of bicycle infrastructure in Canada.

Types of bicycle infrastructure and safety factors

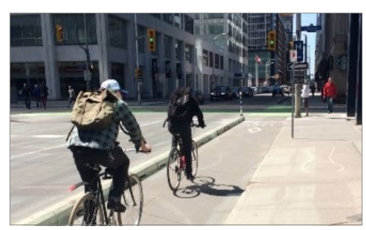
The project studied the observed and perceived safety of bicycle facilities along roadways, bicycle intersection treatments, and other factors influencing bicycle safety as listed below.

Bicycle facilities along roadways

The bicycle facilities considered in this study are:

- Off-road bicycle pathway
- Off-road multi-use pathway
- Protected bicycle lane or cycle track
- Buffered bicycle lane
- Painted bicycle lane
- Bicycle accessible shoulder
- Major street shared lane
- Bicycle boulevard or neighbourhood greenway
- Advisory bicycle lane

Off-road bicycle pathway



Protected bicycle lane

Bicycle intersection treatments

The bicycle intersection treatments considered in this study are:

- Protected intersection
- Bike box
- Two-stage turn queue box
- Intersection crossing markings
- Cross-rides
- Bend-in intersection approach
- Bend-out intersection approach
- Protected signal phase
- Gates, fencing and bollards

Factors influencing bicycle safety

The following factors were identified as playing a significant role in observed and perceived bicyclist safety:

- Vehicle speed
- Vehicular traffic volume
- Presence of trucks and buses
- Presence of vehicle parking

Study knowledge base

The knowledge base for this report comprises a literature review, an end user survey, a jurisdictional survey and case studies. The following provides high-level findings about each of these components of the study.

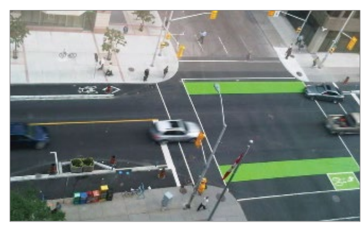
Literature review

The primary objective of the literature review was to understand the safety performance of bicycle infrastructure (including both bicycle facilities along roadways and bicycle intersection treatments) in terms of both observed safety and perceived safety. Specifically, the review developed an understanding of the following: (1) best practices for measuring safety performance of bicycle facilities; (2) related data requirements and safety performance heuristics; (3) bicycle collision trends; and (4) the actual and perceived safety performance of bicycle infrastructure. A total of 153 documents were reviewed. Table E-1 and Table E-2 summarize results in terms of collision risk, collision severity, and perceived safety for each facility type and intersection treatment type, respectively, as documented in the literature.

Painted bicycle lane

Major street shared lane

Protected intersection



Two-stage turn queue box

Cross-rides

Table E-1: Safety outcomes by bicycle facility type

Facility type	Collision risk	Collision severity	Perceived safety
Off-road bicycle facility	●	○	●
Off-road multi-use path	●	□	●
Protected bicycle lane (one-way)	●	□	●
Protected bicycle lane (two-way)	○	□	●
Buffered bicycle lane			●
Painted bicycle lane	○	□	○
Bicycle accessible shoulder			
Major street shared lane	□	□	□
Bicycle boulevard	○	○	
Advisory bike lanes			

● Well supported positive safety outcome
○ General positive safety outcome
△ Neutral outcome
□ General negative safety outcome
■ Well supported negative safety outcome
Blank cells indicate limited research available

Table E-2: Safety outcome by bicycle intersection treatment types

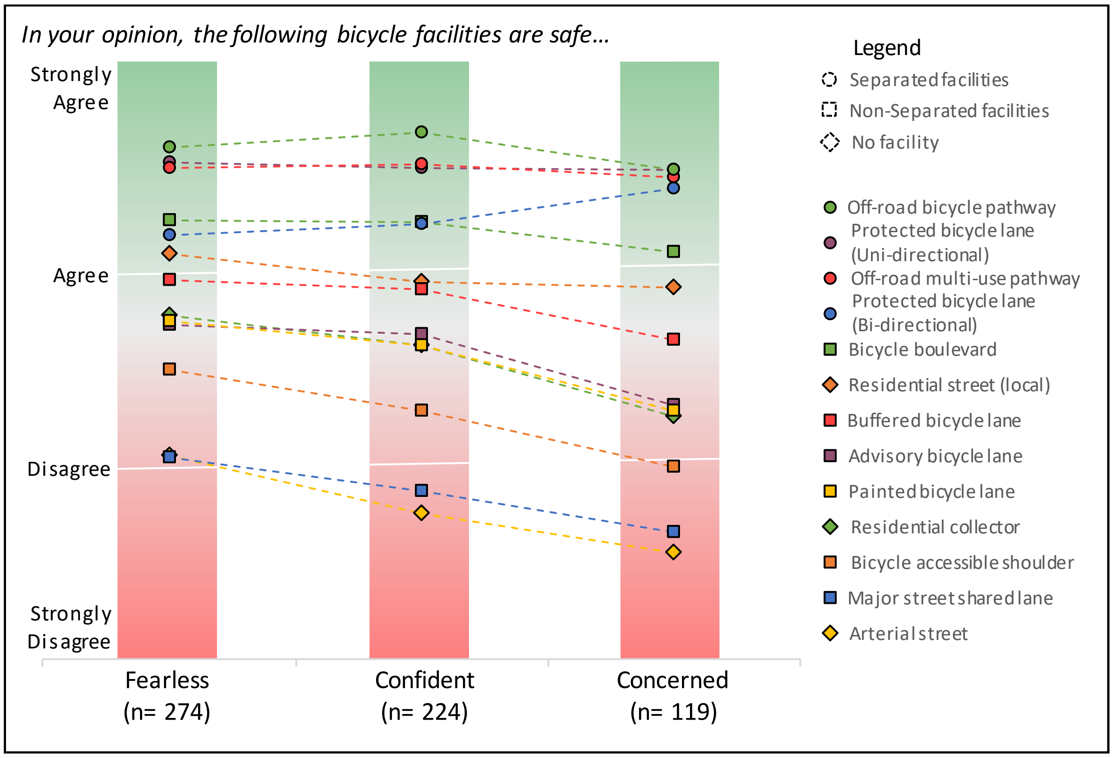
Intersection treatment type	Collision risk	Collision severity	Perceived safety
Protected intersection		○	
Bike box	●		○
Two-stage turn queue box	○		○
Intersection crossing markings	○, □*		○
Cross-rides	○		
Bend-in, bend-out approach			
Protected signal phase	○		
Gates, fencing, bollards			

● Well supported positive outcome
○ General positive outcome
□ General negative outcome
■ Well supported negative outcome
**Various results*
Blank cells indicate limited research available

End user survey

The objective of the end user survey was to investigate how the bicycling community (adults and youth) perceive the safety performance of different types of bicycling infrastructure. Based on responses from nearly 700 bicyclists who self-identify as either fearless, confident, concerned, or youth, the survey found that separated facilities are perceived as safe, followed by lower classification streets with or without a facility, higher volume streets with continuous facilities (e.g. painted bike lanes), and finally, higher classification streets with intermittent (major street shared lanes) or no facility. Figure E-1 shows how safe the bicycling community perceives each bicycle facility to be in the context of all the studied bicycle facility types.

Figure E-1: End user survey results



Jurisdictional survey

The objective of the jurisdictional survey was to understand the current state of Canadian practice with regards to bicycle infrastructure safety. The following was learned from the survey:

- There are three guidelines that are commonly used by Canadian jurisdictions, which provide a benchmark of bicycle infrastructure selection criteria and design: (1) TAC (2017) *Geometric Design Guide for Canadian Roads* (GDG), 4th edition; (2) TAC (2012) *Bikeway Traffic Control Guidelines for Canada*, 2nd edition; and (3) NACTO (2014) *Urban Bikeway Design Guide*, 2nd edition.
- The most implemented bicycle facilities in Canada are off-road multi-use pathway and painted bicycle lanes. Bike accessible shoulders and major street shared lanes were identified as the third and fourth most commonly-implemented facilities by all responding jurisdictions. Bike accessible shoulders are particularly popular in provincial/territorial jurisdictions. Protected

bicycle lanes and buffered bicycle lanes are commonly used by large municipalities but less commonly-used by small municipalities and provinces/territories.

- The most implemented intersection treatments by all respondents are gates, fencing, and bollards. Cross-rides are the second most commonly used intersection treatment by responding large municipalities. Other common intersection treatments in large municipalities are bike boxes, intersection crossing markings, and bend-in intersection approaches. Intersection crossing markings and bend-in intersection approaches are the most common intersection treatments used by small municipalities and provinces/territories.

Case studies

The purpose of these case studies was to obtain a better understanding regarding the safety performance of different types of bicycle facilities based on experiences from Canadian and international jurisdictions. This understanding was an important part of the information to consider in the flow chart development and gap analysis of this project.

The 13 case studies revealed that knowledge about the safety performance of different bicycle facilities is limited in Canada. Part of the reason is that not many formal evaluations have been conducted by jurisdictions once facilities are installed, which posed a challenge for situations where the case study relied on secondary research.

One of the challenges associated with many of the case studies was the lack of available data or information to properly assess the safety performance of the facilities. The following challenges were encountered regarding work based on secondary research:

- Not many formal evaluations were publicly or readily-available.
- Some of the available evaluations were missing important information such as traffic volumes, public opinion, or even collision data.
- Some of the evaluations were several years old.
- Some of the evaluations were not rigorous enough.
- Unless specifically analyzed as part of a study, no information about the safety performance of facilities on segments versus intersections was available.

In situations where the case study relied on primary research, the following challenges were encountered:

- There is a significant lack of all types of data for post-installation of facilities, including for older facilities.
- In some instances, there is neither before nor after data associated with a facility.
- In some cases, jurisdictions have stopped collecting data post-installation and the only available data is limited and old.
- No formal information exists on public opinion regarding bicycle facilities.

Facility selection flow chart

One of the objectives of this project was the development of a flow chart to highlight key steps involved in the decision-making process when selecting a bicycle facility or intersection treatment from the safety perspective. The development of this flowchart was based on four principal sources of information: (1) the comprehensive review of literature conducted for this project; (2) the jurisdictional survey; (3) lessons learned from the case studies; and (4) the end user survey.

Because this flow chart is based on the safety performance of facilities and treatments, it was important to focus on methods that consider exposure-related risks associated with the decision-making process, as well as concepts from the road safety management process with explicit consideration of cyclists. The concept of safety performance was defined in terms of expected collision frequency, and observed collision frequency and severity, where expected collision frequency is determined as a function of traffic exposure and roadway characteristics using safety performance functions (SPFs), and observed collision frequency and severity is defined as the number of collisions recorded by type and severity per unit of time on a given road segment or intersection.

As shown in Figure E-2, a speed-volume envelope was developed that includes seven distinct bicycle safety environments (domains) of 85th percentile speed and vehicular volume.

Based on the factors that were found to impact bicyclist safety and comfort, a series of flowcharts were developed considering the key factors, such as that shown in Figure E-3. Other factors are addressed in a series of templates provided for each of the domains in Figure E-2.

A safety performance evaluation tool was also developed to evaluate safety performance for all domains.

Figure E-2: Speed-volume envelope

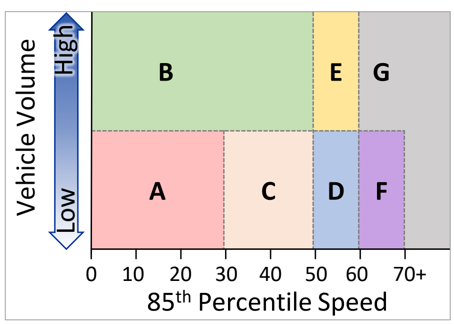
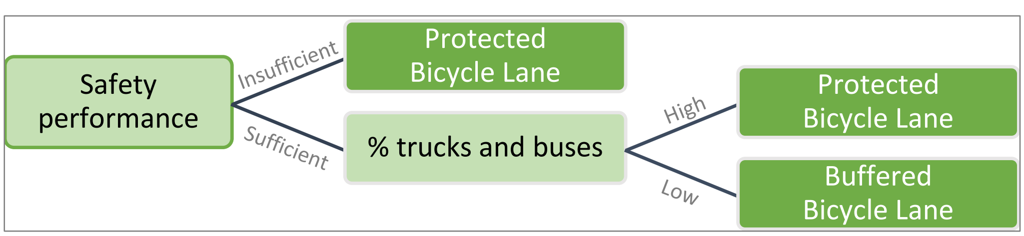


Figure E-3: Domain B Flowchart – Low vehicular speed and high traffic volume

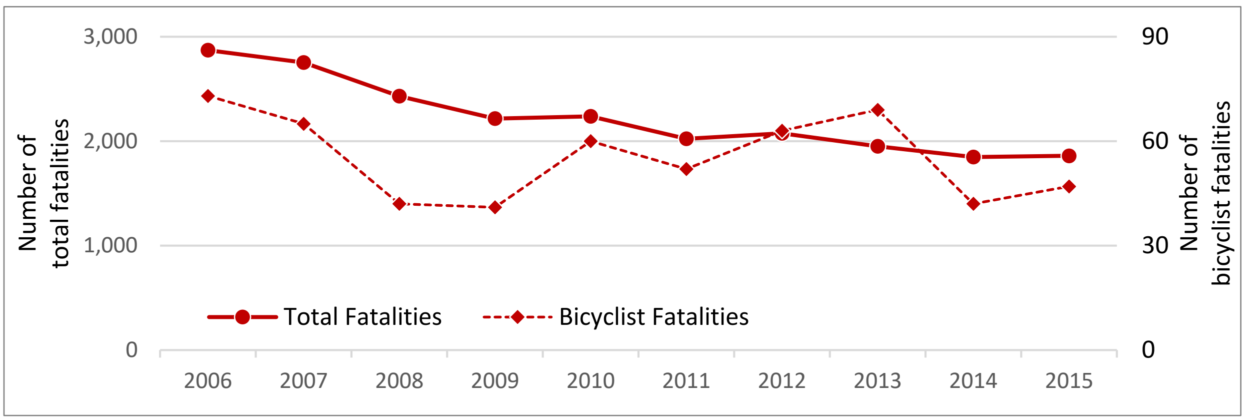


1. Introduction

Bicycling has been demonstrated to reduce a wide range of chronic diseases such as heart disease, diabetes and asthma, while also improving mental health outcomes. The increasing popularity of bicycling as a mode of travel in Canada has resulted in the extensive development of new bicycle infrastructure in many Canadian jurisdictions. A primary goal of bicycle infrastructure is to encourage bicycling to improve public health in a safe and equitable manner, while improving the efficiency of the transportation network inclusive of all modes.

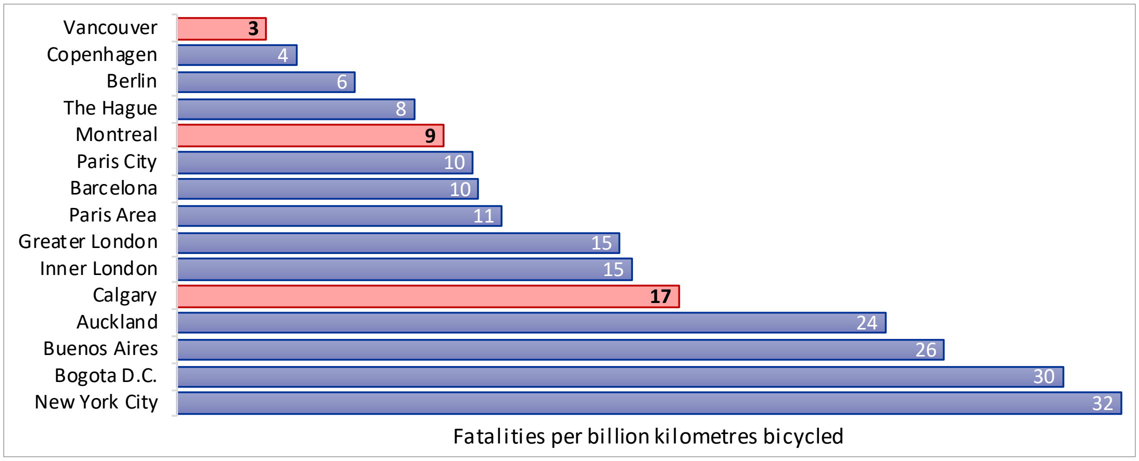
For the last 20 years, governments across North America have been working to increase bicycling as a mode of transportation to improve sustainability, with stronger growth since 2010 (Buehler & Dill, 2016). This has led to an increase in bicycle infrastructure in Canada and, in turn, an increase in the number of bicyclists; however, despite the increase in the number of bicyclists and the potential for more collisions due to the increased exposure, the overall trend of number of injuries and fatalities between 2004 and 2015 decreased in Canada (Ramage-Morin, 2017). In addition, the proportion of bicyclist fatalities relative to the number of total fatalities has remained relatively unchanged over the 10-year period at about 2.5% per year. Figure 1-1 shows the proportion of bicyclist fatalities to total fatalities in Canada between 2006 and 2015.

Figure 1-1: Proportion of bicyclist fatalities to total fatalities in Canada (2006-2015) (Transport Canada, 2017)



The Organization for Economic Cooperation and Development (OECD) International Transport Forum, as part of the Safer City Streets initiative, compared urban road safety across participant cities worldwide to assist member countries in benchmarking their urban road safety performance. Figure 1-2 shows how three Canadian jurisdictions (Vancouver, Montreal and Calgary) compared to other international jurisdictions in regard to the number of bicyclist fatalities per billion kilometres bicycled (Santacreu, 2018). It should be noted that while fatalities per distance bicycled is a preferred metric, bicycle volume data collection is not necessarily comprehensive and therefore network wide estimates of bicycle distance travelled may lack accuracy. In addition, the methods used to estimate network wide bicycle distance travelled may vary significantly between cities.

Figure 1-2: Bicycling fatality rates in selected OECD cities, 2011-2015 (Santacreu, 2018)



Considering these trends and given the continued effort of Canadian agencies to expand their bicycling networks, there is recognition that a lack of knowledge exists regarding the safety performance of bicycle facilities. Many of the readily available safety evaluations of existing bicycle infrastructure (comprising facilities along road segments and intersection treatments) documented in the literature have been focused on U.S. or other international locations that may or may not be applicable to Canada. As a result, it is important to understand the safety performance of different types of bicycle facilities and bicycle intersection treatments in the Canadian context so that more informed decisions can be made by Canadian practitioners regarding the type of infrastructure to implement for different situations. Having a better understanding of the safety performance of each facility type and intersection treatment type in various circumstances will enable a more robust consideration of safety in the bicycle road infrastructure selection process.

1.1 Project objectives and scope

This project characterizes the safety performance of various bicycle infrastructure options within Canada to help practitioners evaluate the potential safety performance of new bicycle infrastructure. The following are specific project objectives:

1. To identify appropriate methods, measures and heuristics to:
    a. Objectively quantify the actual safety performance of different types of bicycle facilities and intersection treatments.
    b. Assess perceived safety of different types of bicycle facilities and intersection treatments.
2. To identify the data requirements to undertake these types of evaluations so that Canadian road authorities can:
    a. Apply the methods and measures selected to determine the actual safety performance and perceived safety of existing bicycle infrastructure facilities and intersection treatments in their respective jurisdictions.
    b. Assess the applicability and predict the safety performance of other potential future bicycle facility/treatment options prior to implementation in Canada.

3. To identify principal types of bicycle infrastructure projects that have been undertaken over the past decade in:
   a. Canadian cities (i.e. low-speed roadways which may have high volumes of people walking, bicycling and travelling by motor vehicle)
   b. Suburban and other rural Canadian settings (i.e. roadways with variable operating speeds, having potentially low-to-moderate volumes of people walking and bicycling mixed with variable motor vehicle volumes)
   c. Canadian highway rights-of-way (i.e. high-speed roadways where travel volumes for all road users may correspond to either an urban, suburban/ex-urban, or rural context).
4. To document and quantify the outcomes of installations encompassing different types of bicycle infrastructure improvements in Canada and elsewhere related to:
   a. The actual safety and perceived safety/level-of-comfort of bicyclists
   b. The numbers of bicycle trips and usage on the improved infrastructure.
5. To develop a method for considering "risks" (within the context of exposure) within the decision-making process for facility/treatment selection.

The scope of this project is specific to the bicycle infrastructure discussed in Section 1.5.

1.2 Study methodology

The contents of this report are based on the following:

- A literature review
- An end user survey
- A jurisdictional survey
- Case studies of Canadian and international bicycle facilities
- Canadian academic community engagement

1.2.1 Literature review

The primary objective of the literature review was to understand the safety performance of bicycle facilities along roadways and bicycle intersection treatments in terms of both actual safety and perceived safety. Specifically, the review assisted in the development of an understanding of the following: (1) best practices for measuring safety performance of bicycle facilities; (2) related data requirements and safety performance heuristics; (3) bicycle collision trends; and (4) the actual and perceived safety performance of bicycle infrastructure.

The scope of the literature review was focused on bicycle infrastructure types identified by the project team and steering committee, which are shown and defined in Section 1.5. In addition, other factors affecting bicycle safety, such as roadway grade, were considered as they relate to the safety performance of bicycle infrastructure.

The Transportation Research Information Database (TRID) was used to conduct a comprehensive search for relevant literature published internationally in the last 10 years. TRID is a database of research and studies that includes the Transportation Research Information Services (TRIS) Database and the Office of

Economic Cooperation and Development (OECD) Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. TRID contains over one million records of transportation research worldwide. Results from this search identified approximately 438 documents using broad search criteria. These documents were sourced from: (1) engineering and scientific periodicals and journals; (2) conference proceedings; and (3) readily available government and industry reports.

The abstracts of the initial 438 documents were reviewed for relevance and 153 were selected for further review and inclusion in the literature review summary provided in Appendix A.

1.2.2 End user survey

The objective of the end user survey was to investigate how the bicycling community and different types of bicyclists (fearless, confident and concerned) perceive the safety performance of different types of bicycling infrastructure.

The end user survey was published using SurveyGizmo and distributed to 38 bicycling organizations across Canada, who were in-turn asked to distribute the survey to their membership. A total of 625 responses were received from across the country. The survey results are included in Appendix B.

When responses from this survey were analyzed, it was deemed beneficial to augment the information collected by investigating opinions of youth (school children in grades 7, 8 and 9) with respect to perception of safety and comfort when riding their bicycles in different environments. An end user youth survey was developed and distributed to gather this information. The end user youth survey (also included in Appendix B) was distributed to 360 schools in Manitoba in January 2019. These schools were identified as housing Grade 7, 8 or 9 students and for which contact information was available. A total of 86 responses were received from youth in Grade 7, 8 or 9 in Manitoba.

One limitation of the end user youth survey is its geographic coverage, having been sent only to schools in Manitoba. However, given the time and budget limitations of the project, it was agreed by the steering committee that, although limited in scope, the findings from this survey could still provide some insight into the safety and comfort perception of children in this age group, particularly given the observed lack of youth participants in the end user survey.

1.2.3 Jurisdictional survey

The objective of the jurisdictional survey was to understand the current state of Canadian practice with regards to bicycle infrastructure safety. Specifically, the jurisdictional survey was intended to answer the following questions:

- What are principal types of bicycle infrastructure (including facilities along road segments and intersection treatments) being implemented in Canada?
- What are the sources of bicycle exposure and safety data being collected by Canadian jurisdictions?
- What type of bicycle exposure and safety data is being collected to complete safety evaluations of bicycle infrastructure?
- How are Canadian jurisdictions deciding which bicycle infrastructure to implement and what input variables do they use?

Once the jurisdictional survey content was finalized, it was published using SurveyGizmo online survey software and a link to the survey was provided to respondents. The survey was distributed online to about 240 TAC member jurisdictions and to individual members of the Canadian Institute of Transportation Engineers (CITE). The survey questions are provided in Appendix C and the summary of findings is included in Chapter 4 of this report.

1.2.4 Case studies of Canadian and international facilities

The objective of this part of the methodology was to conduct 13 case studies to assess and quantify the safety performance of selected bicycle facilities across Canada and internationally. Case studies are typically used as an exploratory mechanism to bring forward new knowledge, or to confirm existing knowledge, about situations or issues that would otherwise be difficult to explain or understand if a larger population would have to be analyzed. In addition, for the purposes of this project, case studies were also used to highlight successes or other experiences resulting from the implementation of different types of bicycle facilities in various settings.

A combination of primary and secondary research was used to conduct the case studies. Four of these were based on primary research and the remaining nine were based on secondary research. The case-studies are provided in Appendix D and results are summarized in Chapter 5 of this report.

1.2.5 Canadian academic community engagement

The Canadian academic community was engaged to identify any on-going and upcoming relevant research in bicycle safety as it relates to bicycle infrastructure. The knowledge obtained from this undertaking was used to:

- Augment the literature review
- Enhance the end user survey questionnaire
- Inform the case studies

A total of 51 academic professionals were included in the engagement process, which comprised the following two questions:

1. Are you currently (or will soon be) undertaking any research to evaluate the safety performance (either perceived or observed) of bicycle infrastructure? (e.g. painted lanes, separated lanes, two-way facilities, intersection treatments, etc.). If the answer is yes, could you please provide a brief description of what the research entails? (e.g. purpose, objectives, scope, location, project duration, expected outcomes).
2. Are you aware of any current research being undertaken in Canada on the above issue? If yes, could you please provide some information about it? (e.g. describe it as much as possible or let us know who to contact or how to get more information about it).

Appendix E presents survey findings.

1.3 Intended audience

This report is designed as a resource document for Canadian jurisdictions, practitioners, academics and other groups interested in the safe accommodation of bicyclists within the transportation network. The report is based on a comprehensive review of literature, a jurisdictional survey, a series of local and international case studies, and an end user survey. In addition, this report contains a facility selection flowchart that can assist practitioners to better inform the selection of a suitable bicycle facility. While the flowchart is not intended to function as a guideline, it does assist in raising issues to consider in the selection of bicycle facilities and intersection treatments.

1.4 Report organization

This report is organized into several chapters.

Chapter 2 provides an overview of the *Highway Safety Manual* (AASHTO, 2010), the various safety study methods that are used to evaluate bicycle safety performance, and the data required to complete these bicycle safety evaluations.

Chapter 3 presents key findings of a comprehensive review of literature regarding the observed and perceived safety performance of various bicycle facilities and intersection treatments. The chapter also presents findings regarding the end user survey conducted as part of this project, which addresses the question of perceived safety for the various bicycle facilities and intersection treatments of interest to this study.

Chapter 4 presents results from the jurisdictional survey about the state-of-the-practice in Canada regarding commonly used bicycle design guidelines, the extent of implementation of bicycle facilities, the extent of implementation of bicycle intersection treatments, bicycle safety data collection and evaluation, and bicycle infrastructure selection practice.

Chapter 5 presents a summary of findings regarding 13 case studies conducted as part of this project to assess and quantify the safety performance of selected bicycle facilities across Canada and internationally. It also identifies lessons for consideration in the development of the facility selection flowchart.

Chapter 6 discusses the development and application of a flowchart that can assist practitioners in providing considerations to better inform the selection of a suitable bicycle facility.

Chapter 7 presents a discussion of the findings of this study with respect to data, information and knowledge gaps about bicycle infrastructure safety. This chapter also provides insight into options that can help close these gaps.

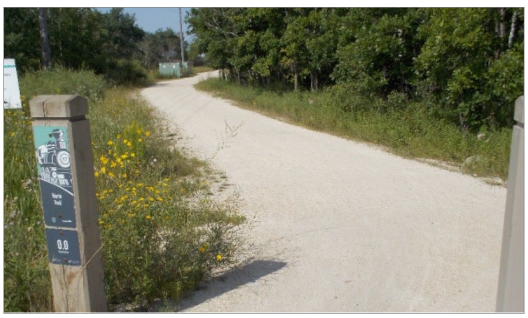
Appendices A through E referenced in this report are available for download from TAC's online publication catalogue.

1.5 Bicycle infrastructure definitions

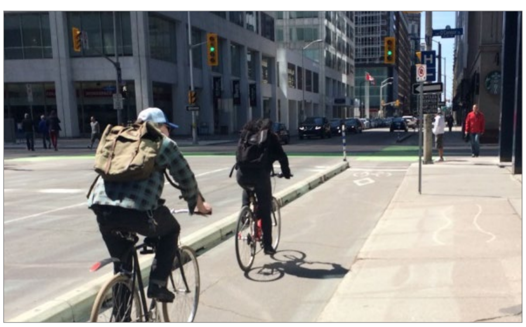
The following are definitions used in this study with respect to bicycle facilities along roadways and bicycle intersection treatments. This is what comprises the bicycle infrastructure considered in this report.

1.5.1 Bicycle facilities

Off-road bicycle pathway – Pathways that are physically separated from motor vehicles and provide enough width and supporting facilities to be **used for cycling only**. These pathways can be paved with concrete, asphalt, or may be surfaced with stone dust, fine limestone, or gravel screenings.



Off-road multi-use pathway – Pathways that are physically separated from motor vehicles and provide enough width and supporting facilities to be **used for cycling and walking**. These pathways can be paved with concrete, asphalt, or may be surfaced with stone dust, fine limestone, or gravel screenings.



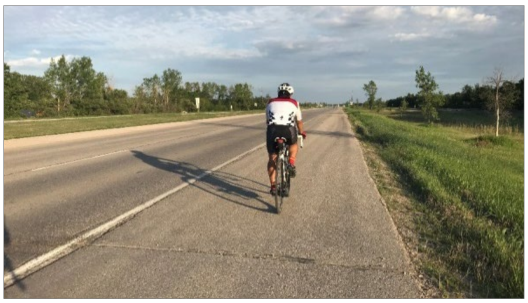
Protected bicycle lane or cycle tracks – Protected bicycle lanes are located within the road right-of-way, but are physically separated from motor vehicle travel lanes by concrete curbs, planters, etc. They can be designed to provide either uni-directional or bi-directional travel. These lanes may be further separated from traffic by a parking lane.

Google Street View

Buffered bicycle lane – Buffered bicycle lanes provide more protected space for bicycling than a painted bicycle lane, typically through a painted buffer or "shy" zones on one or both sides of bicyclists. Plastic posts can be used to delineate the lanes. These lanes may be further separated from traffic by a parking lane.

Google Street View

Painted bicycle lane – Painted bicycle lanes are separated lanes that are designated exclusively for bicycle travel and demarcated by pavement markings.



Bicycle accessible shoulder – Where intended for bicyclist use, and provided enough width is available, paved shoulders on the edge of roadways can serve as a functional space for bicyclists in the absence of other facilities with more separation or delineation.

Major street shared lane – Shared use lanes provide direct routes for experienced bicyclists along the outer travel lane of a roadway. While bicyclists mix with motor vehicle traffic, they are separate from pedestrians using the sidewalk, where a sidewalk exists. Sharrows are painted on the road surface to remind drivers they must share the road with bicyclists and help position road users on the roadway.

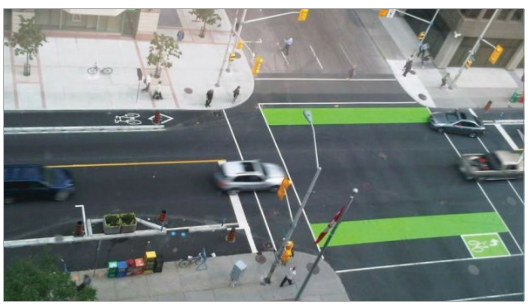
Bicycle boulevards or neighbourhood greenways - Routes on local streets, which include a range of treatments to reduce traffic volumes, slow down traffic, and improve safety for walking, bicycling and driving. A critical component of bicycle boulevards are the treatments implemented at major intersections along the facility. Treatments range from signage, bike signals and pavement markings to varying degrees of traffic calming (speed humps, traffic circles, etc.).

Advisory bike lanes – Advisory bicycle lanes are used on low-volume streets that are too narrow for the installation of conventional bicycle lanes and standard-width travel lanes for motor vehicles. Dashed bicycle lanes are marked on the outside of the roadway with a single narrow two-way vehicle lane occupying the middle of the roadway. The dashed bicycle lane line permits motorists to merge into the bicycle lane to negotiate oncoming traffic when no bicyclists are present.

1.5.2 Bicycle intersection treatments

Protected intersection - Protected intersections extend bicycle lane protection up to and through the intersection, shortening crossings, and physically separating space for through and turning bicycle traffic to wait in an advanced position. Conflicts with turning motor vehicle travel are typically managed with separate signal phases or setback crossings.

Bike box - A bike box is a designated area at the head of a traffic lane at a signalized intersection that provides bicyclists with a visible way to get ahead of queuing traffic during the red signal phase.



Two-stage turn queue box - Two-stage turn queue boxes offer bicyclists a safe way to make left turns at multi-lane signalized intersections from a right-side cycle track or bicycle lane, or right turns from a left-side cycle track or bicycle lane.

Intersection crossing markings - Intersection crossing markings indicate the intended path of bicyclists. They guide bicyclists on a safe and direct path through intersections, including driveways and ramps. They provide a clear boundary between the paths of through bicyclists and either through or crossing motor vehicles in the adjacent lane.

Cross-rides - Cross-rides are crosswalks for bicycles that allow bicyclists to remain on their bicycles and safely cross through intersections. They can be separate from an adjacent crosswalk or combined with a crosswalk.

Bend-in intersection approach - Bend-in intersection approach is achieved by shifting the bicycle lane to be adjacent to the curb-turn lane at the intersection to increase bicyclist conspicuity.

Bend-out intersection approach - Bend-out intersection approach is achieved by shifting the bicycle lane away from the intersection to create space for turning vehicles to wait for bicyclists without impeding other vehicle traffic.

Protected signal phases - A protected signal phase is a phase that does not conflict and is not required to yield to another movement and may be indicated by a green arrow or bike signal.

Google Street View

Gates, fencing and bollards - Use of vertical or horizontal obstructions to force bicyclists to slow or dismount when approaching an intersection, mid-block bicycle crossing, rail crossing, or other situations where high bicyclist speeds are undesirable.

2. Measuring safety performance

Public agencies are tasked with developing bicycle networks that are accessible, convenient and, most importantly, safe. Agencies are required to make these decisions with limited resources and often with limited or no specific knowledge regarding the safety performance of bicycle infrastructure or the methods available to evaluate bicycle safety. For motorized traffic, safety performance has been comprehensively researched and guidelines like those contained in the *Highway Safety Manual* (HSM) (AASHTO, 2010) have been developed to assist practitioners in understanding and evaluating the safety implications of their decisions. While the HSM focuses on motorized traffic, the methods for evaluating safety performance of treatments are directly applicable to bicycle infrastructure safety. This chapter provides an overview of the HSM, the various safety study methods that are used to evaluate bicycle safety performance, and the data required to complete these bicycle safety evaluations.

2.1 Highway Safety Manual

The *Highway Safety Manual* is an industry leading compendium of science-based technical approaches that are designed to guide engineers and other practitioners conducting appropriate safety analyses. The HSM provides step-by-step guidance for engineers and other practitioners to quantitatively evaluate and measure the safety performance of different treatments at various stages (e.g. planning, design, operation, construction and maintenance).

The current version of the HSM provides the following three main tools to help improve safety decision making and knowledge:

1. *Methods for developing an effective roadway safety management program*: A roadway safety management program is the overall process for identifying sites with potential for safety improvement, diagnosing conditions at the site, evaluating conditions and identifying potential treatments at the sites, prioritizing and programming treatments, and subsequently evaluating the effectiveness of the programmed treatments at reducing collisions.
2. *A predictive method to estimate collision frequency and severity*: The method can be used to make informed decisions throughout the project development process. An example includes screening potential locations for improvement based on actual versus predicted collision frequency and severity for a specific road type and choosing between alternative roadway designs. The predictive method relies on the use of Safety Performance Functions (SPFs) to estimate the average collision frequency for a specific site and application of Collision Modification Factors (CMFs) to adjust the average collision frequency for alternative treatments.
3. *A collection of CMFs for a variety of geometric and operational treatments*: Many CMFs in the HSM have been developed with rigorous before/after studies that can reduce regression-to-the-mean bias.

Unfortunately, the current version of the HSM does not explicitly discuss bicycle safety. DiGioia et al. (2017) report that there are limited studies discussing the impact of bicycle infrastructure and most do not produce robust enough results to draw concrete and meaningful conclusions. The lack of quality collision data and exposure data has precluded the development of SPFs for bicycle facilities in the HSM.

However, work is currently underway to develop bicycle SPFs for the second edition of the HSM due for publication in 2020 (NCHRP, 2018).

Two key elements in the HSM are Safety Performance Functions (SPFs) and Collision Modification Factors (CMFs).

Safety performance functions are statistical "base" models that are used to estimate average collision frequency for a facility type (e.g. urban and suburban arterials) with specific base conditions (e.g. cross section). The SPFs are a function of exposure, which is often the annual average daily traffic (AADT) volume as well as facility length when roadway segments are being evaluated. An example of an SPF model equation used to estimate average collision frequency (N_{SPF}) is:

$$N_{SPF} = AADT \ \times 365 \ days/yr \ \times 10^{-6} \ \times e^{-0.4865}$$

The statistical model is a regression equation based on the negative binomial distribution to accurately model the natural fluctuation of collisions. More information on the statistical techniques of developing SPFs is provided in the HSM (AASHTO, 2010).

Collision modification factors are multiplicative factors typically used to estimate the expected number of collisions after implementing a certain treatment at study locations. The CMF is multiplied to the base number of collisions such that:

$$\textit{Expected \# collisions (safety performance)} = \textit{Base \# of collisions (SPF)} \times (CMF)_1 \times \ldots \times (CMF)_n$$

CMFs are used for various reasons, including: (1) estimating the safety effects of various treatments; (2) comparing safety benefits among various alternatives and locations; (3) identifying cost-effective strategies and locations in terms of collision effects; (4) checking reasonableness of evaluations (e.g. compare new analyses with existing CMFs); and (5) checking validity of assumptions in cost-benefit analyses. (Gross et al., 2010).

If a CMF is greater than 1.0, this indicates an increase in collisions after the implementation of a certain treatment. However, if a CMF is less than 1.0, this indicates a reduction in collisions after the implementation of a given treatment, which is a desirable circumstance. As an example, a CMF of 0.8 for a treatment indicates an expected safety benefit of a 20% reduction in collisions after implementation of the treatment. A CMF of 1.2 for a treatment indicates a 20% increase in collisions after implementation of the treatment.

To develop or apply CMFs, the HSM statistical method requires a large amount of collision data, exposure/volume data, and roadway characteristic data. These three data categories are discussed in Section 2.3.

2.2 Safety study methods

When it comes to performance evaluation, studies fall into two categories:

- Experimental studies, which are planned where treatment sites are selected randomly before implementation
- Observational studies, which are planned where treatment sites are selected from the existing roadway system

Experimental studies are rarely feasible in road safety research because the decision to implement safety treatments is made based on short-term collision history or other priorities (e.g. funding, political will, public pressure) rather than completing an experiment (AASHTO, 2010). In addition, there are perceived ethical concerns with experimentation in road safety (FHWA, 2010). As a result, observational studies are the more prevalent source of safety effectiveness and the focus of this section.

Observational studies refer to the overall classification of a group of studies that utilize data collected for treatments that have been implemented by jurisdictions as a result of their normal course of actions based on their unique set of priorities and influences. The types of studies that fall under the 'observational study category' are before-after studies and cross-sectional studies.

In general, before-after observational studies with a comparison group, as opposed to a simple (naïve) before-after observational study, are recommended by the HSM. Statistical methods like the empirical Bayes method can be used to control for changes in traffic volume and regression-to-the-mean effects present in before-after study data. Before-after studies that use the full Bayes or empirical Bayes methods are considered the strongest in terms of the accuracy and reliability of their results and conclusions (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017). An adequate adjustment period is required after a treatment has been implemented to allow for the novelty of the modified environment to subside and traffic volumes (including bicycle traffic) to stabilize. The adjustment period is unique to each environment.

Cross-sectional studies are useful when there is insufficient data (or sample size) from before or after treatment implementation to conduct before-after studies. These studies rely on data collected at existing facilities with slightly different treatments (e.g. arterial roadways with painted bicycle lanes versus arterial roadways with protected bicycle lanes). There are four types of cross-sectional studies (DiGioia et al., 2017):

- Regression cross-section studies use various regression models to statistically compare the effects of different locations.
- Non-regression cross-section studies directly compare the effects of different locations.
- Case-control studies rely on cross-section study data but select study sites based on collision outcome status (e.g. collision or no collision) rather than the presence of a treatment; therefore, in the absence of matching techniques they may not produce results for the targeted infrastructure.
- Cohort studies estimate relative risk which is a direct estimate of CMFs; however, they are uncommon in road safety and not discussed in this section.

Few bicycle studies found in the literature use the empirical Bayes before-after study approach, which is recommended for developing collision modification factors by the HSM (AASHTO, 2010). Case studies and other exploratory analysis that do not rely on rigorous safety study methodologies are the most popular study type, which reveals the exploratory nature of current bicycle infrastructure safety research. In general, case studies produce results for specific locations but lack the statistical rigor to apply to other similar locations. Of the rigorous study methods, cross-section regression studies are the most common, probably because there are an insufficient number of sites for before-after studies with comparison groups.

The following sections discuss each of these study methods and provide more details about what the literature says regarding their strengths, weaknesses and overall performance.

2.2.1 Simple (naïve) before-after study

The simple (naïve) before-and-after study is the simplest (or perhaps most simplistic) method that has been used to evaluate the impact of a treatment. This method compares collision frequency before the implementation of a treatment to collision frequency after the implementation of a treatment. The change in collision frequency between the two periods is presented as the treatment effect. The technique is unable to separate the treatment effect from the other effects due to the possible regression-to-the-mean bias and the traffic volume changes over the study period. Although this method requires the least amount of data (it only requires collision frequency data during study period), this method is not considered as a rigorous method in estimating a treatment effect and often produces an inflated treatment effect. As a result, this method is no longer recommended for estimating the safety performance of a treatment (ITE, 2009).

2.2.2 Before-after study with comparison group

This type of study is like the simple before-after study, however, for this study type an untreated comparison group with similar site characteristics to the treated group is included to account for changes in collisions that are possibly unrelated to the treatment (e.g. changes in traffic volume). In other words, changes within the comparison group before and after a treatment is implemented can be used to estimate the expected number of collisions in the treatment group had no treatment been implemented. This method does not account for regression-to-the-mean unless collision frequency is used to match the comparison sites to the treatment sites, and it is not recommended (FHWA, 2010).

2.2.3 Empirical Bayes (EB) before-after

Unlike the simple before-after study, the empirical Bayes (EB) before-after study is designed to consider the regression-to-the-mean bias and the traffic volume changes that occurred during the study period. As a result, this method usually produces lower treatment effect compared to the result from simple before-after studies. The EB before-after study uses the expected number of collisions (the combination of predicted number of collisions from safety performance functions (SPFs) and observed number of collisions from a study site) as an input to estimate the number of collisions had the treatment not been applied (AASHTO, 2010). This value is then compared with the observed number of collisions after the treatment period to produce the treatment effect. The data requirement for this method is much heavier than for the simple before-after study. EB before-after study requires traffic volumes for the study period as well as relevant safety performance functions, which may or may not be readily available, for the study sites (FHWA, 2010).

2.2.4 Cross-section regression

Cross-sectional studies can be a useful method for estimating treatment effects, particularly if there are insufficient locations where a treatment was applied to conduct a rigorous before-after study. For example, there may be few locations where a major street shared lane was upgraded to a buffered bicycle lane but many locations with a sharrow and many locations with a buffered bicycle lane. In this case, a rigorous before-after study that would be expected to produce credible results is not practically feasible due to a lack of treatments sites. A cross-sectional analysis based on a regression model could be the second-best solution for this circumstance. With the rather strong assumption that developed regression models can account for all (or at least key) input variables that may affect safety, practitioners use the regression model parameters to estimate the changes in collisions that result from a unit change in a specific variable. The amount of data required can be significant because the regression model may identify many key variables that must be represented adequately by the treatment sites (FHWA, 2010).

2.2.5 Cross-section non-regression

Cross-section non-regression studies are like cross-section regression studies except they do not use regression models to account for all variables that affect safety. These studies cannot be used to compare the effects across different locations. Instead they compare effects of the locations studies directly (e.g. simply comparing the number of collisions) (DiGioia, Watkins, Xu, Rodgers & Guensler, 2017).

2.2.6 Case-control

Case-control studies are based on cross-sectional data, but they are not the cross-sectional studies described in Section 2.2.4. A typical cross-sectional study selects study sites based on the condition (e.g. presence or absence) of specific variables (e.g. paved or unpaved) or based on specific classifications of roadways (e.g. arterial, freeway) or types of intersections (e.g. signalized or un-signalized) regardless of the status of having a collision or not. Case-control studies select study sites based on outcome status (e.g. collision or no collision) and then determine the prior treatment (or risk factor) status within each outcome group. In this situation, case sites represent the sites with treatment and control sites represent the site without treatment. Case-control studies assess whether exposure to a potential treatment is disproportionately distributed between the case sites and control sites, thereby indicating the safety impact of a treatment. The data requirement for a case-control study could possibly be smaller than that for a regression-based cross-sectional study, but it still requires a substantial amount of information, including the time for implementing treatments, which may or may not be available for all sites (FHWA, 2010).

2.2.7 Meta-analysis

Where there are several past studies showing distinct estimated effects for the same treatment, it is not always straightforward to select a single value to present it as the most suitable effect for the treatment. It may be appropriate to combine the estimates from all relevant studies for the same treatment to obtain the representative effect of the treatment. Meta-analysis is a systematic way of combining treatment effect from various past studies while considering the quality of each study. Elvik (2005) provides an overview of the meta-analysis process. For a meta-analysis to be useful, all the past studies should be similar in terms of outcome measures and study methodology. It is also desirable that the past studies contain the standard error associated with the estimated treatment effect. Elvik (2005) stated that if there are many studies, a meta-analysis may be able to increase the statistical power by combining the individual results into an overall result.

2.2.8 Preferred safety study methods

As discussed in the previous sections, empirical Bayes (EB) or full Bayes before-after methods are recommended by the HSM (AASHTO, 2010) for undertaking observational safety studies. The EB and full Bayes methods lead to the most accurate and reliable results and they lead to defensible roadway design and operational decisions (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017). Other methods typically used for before-after studies are not recommended because they do not account for regression-to-the-mean bias and traffic volume changes that occurred during the study period.

Before-after EB studies are much preferred over cross-sectional studies for developing CMFs. However, in the absence of quality data from a sufficient time period before treatment implementation, cross-sectional studies may be used as an alternative source of knowledge. Cross-section regression and case-control methods are two possible cross-sectional study methods; cross-section regression studies select sites based on treatment and determine the safety outcome while case-control studies select sites based on outcome status (e.g. collision or no collision) and then determine the treatments that impact the outcome. Figure 2-1 shows relative quality and required information associated with the three methods.

Figure 2-1: Safety study methods

EB before-after study

- Sufficient before/after crash and volume data
- Existence of geometrically and operationally similar comparison sites

Cross-section regression study

- Sufficient number of crashes over study period
- Infrastructure and volume data to develop regression model
- Sites based on similar characteristics and treatment status (e.g., with or without)

Case-control study

- Comprehensive infrastructure data to determine impact of treatments
- Sites based on outcome (e.g., crash or no crash). No targeted treatment

2.3 Data requirements for measuring safety performance

To be able to assess the impact of bicycle infrastructure on bicyclist safety or to develop collision modification factors (CMFs), comprehensive data from the following three categories must be available (AASHTO, 2010, pp. 3–8):

- *Facility data* – This includes information about the physical characteristics of the collision site. This may include bicycle facility type, roadway classification, number of lanes, presence of shoulder, shoulder width, roadway segment length, intersection configuration, traffic control, posted speed limit and grade.
- *Collision data* – This includes the data provided in the collision report (often termed 'traffic accident report' or TAR) that describes the overall characteristics of the collision. This may include collision location, date and time, severity, travel speed, type, police charges or tickets

issued, weather conditions when the collision occurred, and information about the roadway condition and those involved in the collision.

- *Traffic volume data* – This includes annual average daily traffic (AADT) volume for all modes being evaluated for each year of the study period. Average daily traffic (ADT) volumes may be adjusted to estimates of AADT. In addition, vehicle or bicycle kilometers travelled (VKT or BKT) may be used for roadway segments. Total entering vehicles (TEV) or traffic volume by turning movement may be desired for intersections when treatments target specific turning movements (e.g. curb radii reduction to slow right-turning vehicles down).

This section discusses methods and limitations associated with collecting bicycle infrastructure data, collision data and traffic volume data.

2.3.1 Bicycle infrastructure data

Bicycle infrastructure data refers to information about the physical characteristics of the site where collisions have occurred. Some of this information is provided in collision reports but may also be from a jurisdiction's roadway inventory database that can be geospatially joined to the collision database through the collision location. Currently, bicycle facilities are not well represented in roadway inventory data, which makes it difficult to study collision causation and bicycle infrastructure safety performance. As such, researchers have had to collect their own facility roadway data, which varies significantly between studies. The following is a list of facility roadway data collected in some of the bicycle infrastructure safety studies completed in Canada:

- Functional classification of street or path
- At intersection or segment
- Along straight segment or curve
- Roadway segment length
- Number of vehicular and bicycle lanes
- Lane width
- Width of the right-most travel lane
- Width of on-street bicycle lane (if exists)
- Median width
- Median type
- Type of parking
- Posted speed limit
- Presence of driveways or service lanes
- Street lighting
- Streetcar or train tracks
- Slope of the surface (grade)
- Driver sight distance
- Presence and width of shoulder

2.3.2 Collision data

Most jurisdictions have well established collision databases that contain basic collision information such as the date/time, location, collision type and injury classification. The source of the data is typically traffic accident/collision reports (TARs) from police records and may be supplemented with hospital and insurance records. TARs often include other collision details about the collision causation that are used to evaluate road safety. However, this causation data often focuses on motorized users and is less relevant for non-motorized users (Karsch, Hedlund, Tison & Leaf, 2012). For example, motorist turning movement is an important indication of collision causation at intersections and commonly collected in TARs, whereas bicycle turning movement is also important but rarely recorded. To overcome the lack of causation data, some research has relied on interviews with hospitalized bicyclists to understand the safety performance of bicycle infrastructure (Cripton et al., 2015; Harris et al., 2013a; Teschke et al., 2012; Wall et al., 2016).

The literature states that regardless of the collision causation data collected, observed or recorded collision data is limited due to the following factors: (1) collision reporting issues; (2) the natural variation and randomness of collisions; (3) changing roadway characteristics; and (4) collision estimation methods (AASHTO, 2010). These are discussed further here.

Collision reporting issues

Bicycle collision under-reporting is a significant issue for bicycle collision data (DiGioia et al., 2017). Overall, a study across 17 countries (excluding Canada and the U.S.) found that an average of approximately only 10% of all bicyclist collisions are reported to police (Shinar, 2018). In addition, frequency-severity indeterminacy and the use of minimum collision reporting thresholds are other collision reporting issues that currently exist.

Research has found that the likelihood that bicycle collisions are reported is dependent on the severity of injury that resulted from the collision where major injuries are reported much more often than minor injuries (AASHTO, 2010). This issue is known as frequency-severity indeterminacy, which represents the difficulty in identifying if a treatment changed the collision frequency or just reduced the number of major injuries which result in fewer collisions being reported. It is important to consider the potential for frequency-severity indeterminacy to influence safety performance results of bicycle infrastructure.

Jurisdictions set a minimum collision reporting threshold that must be met to require that a collision be reported. Canadian jurisdictions usually define this minimum threshold by a specific amount of property damage or the need for a vehicle to be towed from the collision scene. It is important to note that all injury and fatality collisions involving a vehicle are required to be reported; the minimum collision reporting threshold applies to non-injury/fatality collisions. Table 2-1 shows the various minimum collision reporting thresholds for Canadian Provinces and Territories. The table shows that minimum collision reporting thresholds vary throughout Canada, which makes it difficult to compare collision rates between jurisdictions and over time as the thresholds are different. In addition, the value of a collision involving a bicycle may be below the threshold simply because the bicycle is worth less than $1,000 or $2,000 and vehicle damage is minimal.

The need for involvement of a vehicle in collision reporting contributes to gaps in collision databases relative to bicyclist-only collisions and bicycle collisions with other bicyclist or pedestrians. Bicyclist-only collisions are caused by a bicyclist colliding with infrastructure, losing control, or the bicycle itself malfunctioning. In the Netherlands, research indicates that a significant proportion of bicycling collisions are bicyclist-only collisions (in the order of 75% of hospital admissions) (SWOV, 2014). In Canada, underreporting of bicyclist collisions not involving vehicles may represent a significant gap in bicycle collision data. Results from the end user survey indicate that 69% of bicyclists that have been involved in at least one collision while bicycling have collided with a roadway element (e.g. curb or pothole).

Natural variation and randomness of collisions

Collisions are random events that naturally fluctuate over time, which indicates that short-term collision frequencies are not a reliable representation of long-term collision trends at a location. As such, it is difficult to know if a three-year collision frequency represents the average collision frequency at a site or due to natural collision fluctuations.

In addition to natural fluctuations, it is statistically probable that a period of high collision frequency will be followed by a period of low collision frequency and vice versa. This tendency is called regression-to-the-mean and can bias research that relies on short-term collision frequencies. For example, if a treatment is implemented after a naturally low year of collisions the probability that the year following implementation would have a naturally high number of collisions is increased wand may mask the reduction of collisions caused by the treatment, and vice-versa. This underscores the importance of strong long-term or expected collision frequency knowledge. It also highlights the uncertainty of broadly implementing a new facility or treatment type without a firm understanding of its envisioned actual safety effect and the facility's past actual "expected" safety performance.

Table 2-1: Minimum collision reporting threshold by province (adapted from OWMA, 2014)

Province or territory	Applicable statute	Minimum collision reporting threshold[1]	Since
British Columbia	Motor Vehicle Act (249 (1) b)	$1,000	2008
Alberta	Traffic Safety Act (70)	$2,000	2010
Saskatchewan	Traffic Safety Act (253 (4) d)	Tow-away	
Manitoba	Highway Traffic Act (155 (4))	No reporting on property damage	2011[2]
Ontario	Highway Traffic Act (199 (1))	$2,000	2015
Quebec	Highway Safety Code (176)	$2,000	2010
New Brunswick	Motor Vehicle Act (130 (1))	$1,000	
Prince Edward Island	Highway Traffic Act (3 b)	$2,000	2012
Nova Scotia	Motor Vehicle Act (98 (1))	$2,000	2013
Newfoundland	Highway Traffic Act (170 (1))	$2,000	2013
Yukon	Motor Vehicles Act (95 (1))	$1,000	
Northwest Territories	Motor Vehicles Act (261)	$2,000	2011
Nunavut	Motor Vehicles Act (262)	$1,000	

1: represents the minimum collision reporting threshold (excluding injuries/fatalities)
2: clarified the implementation year based on Bill 37 of Manitoba's Highway Traffic Act

Variations in roadway characteristics

Long-term collision data is critical for completing accurate safety performance evaluations. However, long-term collision data that represents a homogenous bicycle facility along a roadway or at an intersection is difficult to obtain because facility elements and operational characteristics change over time. While collision data may be available for 10 years before a treatment is implemented, the traffic volumes and land use adjacent to the bicycle facility may have changed within that period. The HSM presents a predictive statistical method of estimating collision frequency for all study years, which relies on safety performance functions to address this issue, as well as the regression-to-the-mean issue discussed above. This method requires a robust set of facility characteristics, collision, and traffic volume data.

Collision estimation methods

The current state of bicycle infrastructure safety research relies mostly on observed collision frequency for short periods and surrogate safety measures (e.g. vehicle encroachment and bicyclist safety perception) whose relationship with collisions is not well understood. Table 2-2 discusses the various advantages and limitations of methods for estimating the collision frequencies, as detailed in the HSM (AASHTO, 2010).

Table 2-2: *Highway Safety Manual* methods for estimating collisions

Methods for estimating collisions	Advantages	Limitations
Observed collision frequency and collision rate, are historical collision data and are often used for estimating collisions and evaluating the effectiveness of a treatment.	• Well understood by practitioners and most of the public • It is accepted that historical trends will continue to occur in the future • Most jurisdictions maintain a database of historical collisions	• Bicycle collisions are infrequent, under-reported, and may require a long time-period of homogenous conditions which may not be available or easy to achieve given the infancy of implementation for many bicycle facilities in Canada.
Surrogate safety measures can be used as an indirect measure of observed collisions. They may be based on events that precede a collision (e.g. conflict studies that quantify near-misses) or on a causal link to collisions (e.g. age and ability of cycling population).	• Data can be collected as there is no need to wait for collisions to occur. Consequently, this method is more proactive. • May not require a long time-period of data collection and thus can be used on relatively new facilities	• The relationship between collisions and surrogate safety measures is often unproven and may introduce another source of inaccuracy.
Statistical methods have been developed using regression analysis to address regression-to-mean bias and reliably estimate expected average collision frequency for existing roadways, future changes to existing roadways, or new roadway designs. The HSM uses the predictive model which relies on safety performance functions (SPF) to estimate the average collision frequency of the base facility type and the Empirical Bayes Method to adjust model if observed collision data is available.	• Can be used to estimate expected average collision frequency for future changes to existing roadways, and new roadway designs • Accounts for regression-to-mean bias • Does not rely on availability of limited collision data from one specific site • Accounts for non-linear relationship between collision frequency and traffic volume	• Statistically complex to develop.

2.3.3 Traffic volume data (exposure)

The lack of bicycle traffic volume data is a crucial limitation of all bicycle infrastructure safety studies. System-wide bicycle traffic monitoring programs are critical to the provision of adequate bicycle volume data needed for high quality safety performance research. Yet guidance for developing these programs has only just become available and has not seen widespread implementation in Canadian jurisdictions. For example, non-motorized traffic monitoring was first included in the *Traffic Monitoring Guide* (FHWA, 2013), in the *Guidebook on Pedestrian and Bicycle Volume Data Collection* (Ryus, et al., 2014), and in the *Traffic Monitoring Practices Guide for Provinces and Municipalities* (TAC, 2017).

Based on a survey administered for the TAC *Traffic Monitoring Practices Guide* in 2016, only two Canadian jurisdictions of the 28 respondents of the survey, had implemented a scheduled bicycle traffic monitoring program and 11 respondents did not collect any bicycle data (TAC, 2017). Current bicycle traffic data collection efforts are characterized by short duration counts that are collected as needed at locations with high cycling volumes. As a result, data is insufficient to produce an accurate estimate of annual average daily bicycle traffic which is required by the statistical methods to assess the safety performance of any bicycle infrastructure.

Without accurate bicycle traffic data, jurisdictions will not know the actual safety performance of bicycle infrastructure because new treatments may increase both bicycle traffic volumes and collision frequency but, when considered together, the result would be a lower risk of collision per bicyclists (collision rate). An overarching goal of implementing bicycle facilities is to encourage bicycle ridership. Similarly, vehicular volumes increase with time and need to be incorporated in the statistical analysis of the safety performance of the roadway and intersection before and after the implementation of any bicycle infrastructure. Thus, it is critical that jurisdictions collect exposure data so that bicycle infrastructure safety research becomes feasible and of high quality.

The TAC *Traffic Monitoring Practices Guide* (2017) is an excellent resource for jurisdictions developing a system-wide, non-motorized traffic monitoring program.

2.4 Safety performance metrics

Performance metrics are important to allow for the evaluation of transportation infrastructure. If properly developed and applied, they provide a mechanism by which practitioners can objectively plan and prioritize investments, which is essential in an environment that operates within funding constraints and the need for prioritization based on return on investment. In the context of bicycle safety, the application of performance metrics can help practitioners to successfully monitor the performance of various bicycle projects and present the benefits of these projects to elected officials or the public. However, according to Semler et al. (2016), the development of performance metrics specific to active transportation is still in its infancy for many agencies in the U.S., although some are increasingly using bicycle performance measures for a variety of applications, including project prioritization. The same statement can be made for Canadian jurisdictions where some have an established mechanism to evaluate the performance of their bicycle infrastructure, while others are just getting started.

Developing meaningful performance metrics specifically for bicycling is important for the following reasons (Fehr and Peers, 2015):

- To show the benefits of various projects to the public and elected officials
- To track the success of new policies or programs
- To help inform future investment through data-driven measures of success
- To help with the planning, design and implementation of bicycling facilities that improve the built environment
- To help capture the value of new and innovative databases and data collection methods that will inform bicycling infrastructure design and implementation

Performance metrics can be applied to a variety of contexts (e.g. rural vs. urban land use, local or regional geographic coverage, or a variety of planning processes such as project prioritization, comparison of alternatives, benchmarking, scenario evaluation and others). For the purposes of this study, the main contexts of interest are urban and rural land uses, local geographic coverage, and benchmarking (e.g. tracking change over time).

Because no single performance metric by itself can be used to present the overall performance of the system, it is important to develop a series of metrics that are closely aligned with established community goals. For example, if safety and security are community goals, then metrics that evaluate a piece of infrastructure against those goals are needed for proper analysis.

Based on the goals of this study, the performance metrics discussed in this document relate to observed safety, perceived safety and level of comfort associated with bicycle facilities. Table 2-3 illustrates a variety of performance metrics applicable to each of the goals of importance to this study.

Table 2-3: Performance metrics by study goal

Performance metric	Goals		
	Observed safety	Perceived safety	Level of comfort
Kilometres of bicycle facilities Refers to the total distance, expressed in kilometres, of all bicycle facilities in a specified geographic area. The measure can be separated by bicycle facility type (e.g. kilometres of buffered bicycle lanes, protected bicycle lanes, shared-use paths).		✓	✓
Bicyclist average travel time The average time it takes bicyclists to travel a specified distance.		✓	✓
Average trip length by bicycle The average distance or time traveled between an origin and a destination in a given geographical area.		✓	✓
Bicycle collision frequency The measured number of collisions over a given period. This metric is typically categorized by severity (i.e. fatalities, injuries, or property damage only).	✓		
Frequency of conflicts between bicyclists and motor vehicles/pedestrians Refers to alternative metrics to measure a safety problem (e.g. number of conflicts between bicyclists and vehicles or pedestrians) over a given period.	✓	✓	
Bicycle network connectivity Measures the extent of completeness of the bicycle network. It can be measured in terms of the number of gaps that exist in the network or the number of continuous kilometres of bicycle facilities.		✓	✓
User perceptions A measurement of how safe a user feels under various network scenarios. For example, what is the perceived safety of bicyclists when traveling on a buffered bicycle lane vs. a multi-use path or other facility types.		✓	✓
Bicycle volume The measured number of bicyclists at a specified location over a designated period. The measurement is usually based on a count taken at the location of interest.		✓	✓
Bicycle kilometres travelled (BKT) A measurement of the amount of travel for all bicycles in a geographic area (or along a facility or network) over a given period of time, typically a one-year period. It is calculated as the sum of the number of kilometres traveled by each bicycle.		✓	✓

3. Observed and perceived safety of bicycle infrastructure

This chapter presents key findings of a comprehensive review of literature regarding the observed and perceived safety performance of various bicycle facilities and intersection treatments. The chapter also presents findings regarding the end user survey conducted as part of this project, which addresses the question of perceived safety for the various bicycle facilities and intersection treatments of interest to this study. Details of the literature review are included in Appendix A and details of the end user survey are included in Appendix B.

For the purposes of the end user survey, a key definitional issue is the classification of bicyclists based on their self-identified ability. TAC's *Geometric Design Guide for Canadian Roads* (2017) presents the following categories based on research completed in the U.S. (Dill & McNeil, 2013):

- *Strong and fearless* – Bicyclists that will typically ride anywhere regardless of road conditions or weather.
- *Enthused and confident* – Bicyclists who are comfortable riding on all types of bikeways, but usually choose low traffic streets or multi-use paths where available.
- *Interested but concerned* – Bicyclists who typically ride a bicycle on low traffic streets or multi-use paths under favourable weather conditions.

These were used in the end user survey. A fourth bicyclist type, "No-way, no-how" was excluded, as this bicyclist type in effect represents individuals who are not bicyclists.

3.1 Bicycle facilities

The bicycle facilities shown in Section 1.5.1 were included in this study based on their consideration in major bicycle design guidelines such as the *Geometric Design Guide for Canadian Roads* (GDG) (TAC, 2017) and best practices identified by project steering committee members. This section presents results from the literature review and the end user survey on the observed and perceived safety of bicycle facilities.

3.1.1 Literature review findings

Key findings from the literature review regarding each of these facility types are discussed here. In general, there was a limited amount of quality literature to make strong conclusions on the observed safety of bicycle facilities.

Off-road bicycle pathway – The literature indicates that off-road bicycle pathways reduce both severe and less severe collisions with bicyclists compared to no facility (Kaplan & Giacomo Prato, 2015) and they reduce the risk of bicyclist injury when compared to off-road multi-use pathways and major streets with parked cars and no bicycle infrastructure (Teschke et al., 2012).

In terms of perception, the literature indicates that providing physical separation between bicycles, vehicles and pedestrians significantly increases bicyclists' perception of safety and comfort both along roadways (Bai, Liu, Chan & Li, 2017) and at intersections (Ng, Debnath & Heesch, 2017). In North America, results from bicyclist surveys carried out in Vancouver and Michigan indicated that bicyclist perception of safety is positive on off-road bicycle pathways.

Off-road multi-use pathway – The literature indicates that off-road multi-use pathways reduce total collisions by 25% along-side urban six-lane divided highways compared to no treatment (Raihan & Alluri, 2017) and reduce bicyclist injury rate compared to no bicycle infrastructure along major streets with parked cars (Teschke et al., 2012). Regarding injury severity, literature finds that the severity of bicycle collisions is higher when cycling on off-road multi-use pathways than on major streets (Cripton et al., 2015); cycling on the sidewalk has a higher injury severity than cycling on off-road multi-use pathways. Overall, off-road multi-use pathways seem to reduce bicycle collision frequency but increase the risk of a more severe injury in the event of a bicycle collision as compared to a major street with no bicycle facility.

The literature also indicates that bicyclists perceive off-road multi-use pathways to be safe and comfortable when compared to other bicycle facilities (e.g. protected bicycle lanes, painted bicycle lanes and shared lanes) (Ng et al., 2017) and roadways with no bicycle facilities (Winters & Teschke, 2010).

Protected bicycle lane or cycle track – The literature indicates that along roadway segments, one-way protected bicycle lanes have significantly lower risk of bicyclist collisions compared to roadways without bicycle facilities (Harris et al., 2013a; Teschke et al., 2012). Two-way protected or buffered bicycle lanes with parking separation also reduce bicyclist collision risk along road segments and at intersections compared to no facility; however, two-way protected or buffered bicycle lanes without parking separation tend to increase bicyclist collision risk at intersections (Nosal & Miranda-Moreno F, 2012). Conversely, the presence of a protected bicycle lane is associated with an increase in injury severity compared to no bicycle facility (Wall et al., 2016).

The literature indicates that protected bicycle lanes increase a bicyclist's perception of safety both at intersections (Wang et al., 2018) and along roadways (McNeil, Monsere & Dill, 2015; Sanders, 2013; Sanders & Judelman, 2018). The difference in safety perception between protected bicycle lanes and buffered bicycle lanes with vertical deflection (i.e. flexible bollards) was found to be minimal (McNeil et al., 2015). At intersections in Ohio, bicyclists perceived two-way protected bicycle lane approaches to be slightly safer than one-way protected bicycle lane approaches; however, the two-way bicycle facilities also had bicycle signals at intersections which may have influenced the perception of safety.

Buffered bicycle lane - Few studies were found regarding the safety of buffered bicycle lanes. One study by Goodno et al. (2013) analyzed collisions on two, two-way buffered bicycle lanes (one located in the median and one curbside) in Washington, D.C. before and after implementation. The authors found that bicyclist collision frequency increased after the implementation of the bicycle facilities at both sites. However, bicycle collision rate remained constant for the curbside facility. Bicycle collision rate increased for the median facility but mainly due to illegal U-turn activity by motorists.

The literature indicates that buffered bicycle lanes are perceived to be safer for bicycling than roadways with no bicycle facilities (Goodno, McNeil, Parks & Dock, 2013; McNeil et al., 2015; Sanders & Judelman, 2018). When considering perceived safety of child bicyclists, buffered bicycle lanes are perceived to be less safe than separated bicycle facilities but safer than painted bicycle lanes on four-lane roadways (Sanders & Judelman, 2018). The difference in bicyclist safety perception between protected bicycle lanes and buffered bicycle lanes with vertical deflection (i.e. flexible bollards) is minimal (McNeil et al., 2015). Subsequently, the high stated comfort levels of two- to three-foot painted buffers with plastic flexible bollards indicate that the desired increase in bicyclist safety perception may be achieved by relatively affordable treatments (i.e. flexible bollards vs. concrete curbs).

Painted bicycle lane – The literature indicates that painted bicycle lanes reduce bicycle injury and collision frequency when compared to roadways without bicycle facilities (Bhatia et al., 2016; Hamann & Peek-Asa, 2013; Nosal & Miranda-Moreno F, 2012; Park, Abdel-Aty, Lee & Lee, 2015; Pulugurtha & Thakur, 2015; Teschke et al., 2012). This result is supported by research investigating the impact of vehicle encroachment which indicates that painted bicycle lanes increase the distance between overtaking vehicles and bicyclists (Chapman R, 2015; Feng, Bao & Delp, 2018; Mehta, 2015). However, painted bicycle lanes increase collision risk when implemented on two-lane divided highways but decrease collision risk when implemented on 4-lane divided highways (Raihan & Alluri, 2017).

Compared to major streets with parking, the bicycle collision rate decreases with the presence of a painted bicycle lane and significantly decreases if the major street has no parking and a painted bicycle lane (Teschke et al., 2012). At intersections, collision rate decreases with the presence of painted bicycle lanes approaching the intersection (Nosal & Miranda-Moreno F, 2012).

Findings regarding the bicyclist injury severity as a result of painted bicycle lanes are mixed. Painted bicycle lanes seem to increase the risk of bicyclists experiencing more than a mild injury (Wall et al., 2016) but also increase chances of bicyclists experiencing no injury (Bhatia et al., 2016).

The literature indicates that confident bicyclists perceive painted bicycle lanes to be comfortable when compared to no facility (Chataway, Kaplan, Nielsen & Prato, 2014; McNeil et al., 2015). However, non-cyclists do not perceive painted bicycle lanes to be comfortable. There was no difference in bicyclist safety perception of painted bicycle lanes that are 3.75 feet (1.1 meters) wide compared to 6.25 feet (1.9 meters) wide (Sener, Eluru & Bhat, 2009).Other literature suggests that painted bicycle lanes may not operate as intended with the presence of snow on the roadway (Shirgaokar & Gillespie, 2016).

Bicycle accessible shoulder - Bicycle accessible shoulders are most commonly used in rural areas along highways characterized by high vehicle speeds and low vehicle and bicycle volumes. However, there is a gap in research about the safety performance of bicycle accessible shoulders along rural highways.

In general, bicycle accessible shoulders in urban environments are expected to behave like painted bicycle lanes (discussed in the previous section) where bicycle accessible shoulders are not constrained by a curb on the roadway edge. Literature regarding vehicle encroachment as a surrogate measure of bicyclist safety indicates that vehicles travel closer to bicyclists when the bicyclists have a marked lane (i.e. painted bicycle lanes and bicycle accessible shoulders) (Feng et al., 2018). In addition, vehicles tend to travel across a solid centre lane into on-coming traffic (two-lane roadways) more often then they travel across a dashed lane into another lane in the same travel direction (four-lane roadways) (Feng et al., 2018). This finding indicates that vehicles may give more space to bicyclists on accessible shoulders along two-lane roadways rather than four-lane roadways.

Major street shared lane – The intent of shared lanes is to increase driver awareness of bicyclists and assist drivers and bicyclists in safely positioning themselves on the roadway relative to each other in the shared lane and the roadside which may be parked vehicles, curbs, or the paved edge. The position of the sharrow marking in the shared lane, the width of the shared lane, and the presence of parking each have a significant impact on the safety of major street shared lanes for bicyclists (Schimek, 2017). The literature findings are mixed as a result of the large variation of ways that major street shared lanes can be implemented. Overall, major street shared lanes have been found to increase bicyclist collision risk and the risk a bicyclist will experience a more severe injury as result of a collision when compared to major streets with no bicycle facility (Ferenchak & Marshall, 2019; Wall et al., 2016).

Despite the increase in bicycle injury rates, literature indicates that the position of the sharrow marking can influence the position of drivers and bicyclists on the roadway. Specifically, the sharrow marking may increase the operating space for bicyclists by increasing the separation of the bicyclist away from roadside hazards (i.e. parked vehicles and curbs) as well as increasing the separation distance between passing vehicles (Fitzpatrick et al., 2011; Furth & Dulaski, 2011). The separation distance between bicyclists and parking is particularly notable considering that the presence of parking significantly increases the risk of injury to bicyclists (Teschke et al., 2012). The separation between bicyclists and parking is greater with sharrows on multi-lane roadways compared to sharrows on two-lane roadways (Fitzpatrick et al., 2011) and when the sharrow marking is located in the centre of the shared lane (Schimek, 2017). These studies treat the increase in operating space for bicyclists as a surrogate for a reduction in bicycle collision risk due to the potential decrease in collisions with passing vehicles and dooring collisions that result when a bicyclist travels too close to a vehicle door when it is opened. However, a majority of bicyclists may still travel in the “dooring zone” near parked vehicles regardless of the presence of sharrows (Schimek, 2017).

These results suggest that sharrow markings may be effective in positioning bicyclist’ alignment, however, when implemented as a continuous bicycle facility for major street shared lanes they tend to increase bicyclist collision risk and injury severity.

The literature indicates that in general, bicyclists perceive major street shared lanes to be one of the least safe and comfortable bicycle facility types (Ng et al., 2017; Winters & Teschke, 2010). Other literature indicates that major street shared lanes without parking are preferred to major street shared lanes with parking (Winters & Teschke, 2010) and major street shared lanes are perceived to be ineffective during months with snow cover (Shirgaokar & Gillespie, 2016).

Bicycle boulevard – The literature indicates that bicyclist-vehicle collision frequency is significantly lower on bicycle boulevards than riding on arterials (Minikel, 2012; Teschke et al., 2012) and the presence of bicycle-specific signage decreases injury rate (Hamann & Peek-Asa, 2013). Traffic calming measures like directional diverters and traffic circles, are often implemented along bicycle boulevards to reduce vehicle speeds and volumes. The use of directional diverters significantly decreases bicyclist collision frequency while the use of traffic circles with a six- to eight-metre circle diameter significantly increases bicyclist collision frequency (Harris, et al., 2013).

Advisory bike lane - Advisory bicycle lanes are relatively new devices and there is limited research that discusses their safety performance. Literature indicates that vehicles travel closer to bicyclists when bicyclists have a marked lane (i.e. painted bicycle lanes and bicycle accessible shoulders). In addition, vehicles tend to travel across a solid centre lane into on-coming traffic (typically on two-lane roadways) more often then they travel across a dashed lane into another lane in the same travel direction (typically on four-lane roadways) (Feng et al., 2018). This may be the result of motorists being more comfortable crossing into oncoming traffic because they can easily see when they are able to do so rather than shoulder checking to cross a white dashed line into another lane in the same travel direction. This result is positively related to bicycle accessible shoulders because vehicles are required to share a centre lane with oncoming vehicles and encroach into the advisory bicycle lane to pass oncoming vehicles.

Table 3-1 summarizes results from the literature review by the general safety outcome for collision risk, collision severity, and perceived safety for each facility type.

Table 3-1: Safety outcomes by bicycle facility types from literature

Facility type	Collision risk	Collision severity	Perceived safety
Off-road bicycle facility	●	○	●
Off-road multi-use path	●	□	●
Protected bicycle lane (one-way)	●	□	●
Protected bicycle lane (two-way)	○	□	●
Buffered bicycle lane			●
Painted bicycle lane	○	□	○
Bicycle accessible shoulder			
Major street shared lane	□	□	□
Bicycle boulevard	○	○	
Advisory bike lanes			

● Well supported positive safety outcome
○ General positive safety outcome
△ Neutral outcome
□ General negative safety outcome
■ Well supported negative safety outcome
Blank cells indicate limited research available

3.1.2 End user survey results

Results from the end user survey provide insight as to the bicycle facilities that bicyclists perceive to be safer and more comfortable for travel. Figure 3-1 shows how respondents perceive the safety of bicycle facilities based on their self-identified bicyclist type.

As the figure shows, separated facilities (e.g. off-road multi-use path, off-road bicycle pathways, and protected bicycle lanes) are perceived to be the safest bicycle facilities with off-road bicycle pathways being perceived as the safest bicycle facility amongst all bicyclist types. Fearless and concerned bicyclists have a conflicting safety perception of bi-directional protected bicycle lanes. Fearless bicyclists perceive them to be less safe than bicycle boulevards a non-separated facility whereas concerned bicyclists find them to be safer that bicycle boulevards to a degree that is consistent with other separated facilities. Major street shared lanes and arterial streets (major streets with no bicycle facility) were identified by all types of bicyclists as being unsafe. Bicycle accessible shoulders are also perceived to be unsafe, mainly by concerned bicyclists.

In general, separated facilities are perceived as safe, followed by lower classification streets with or without a facility, higher volume streets with continuous facilities (e.g. painted bike lanes), and higher classification streets with intermittent (sharrow) or no facility. As such, the perception of safety appears to follow a hierarchy related to the level of exposure to vehicle traffic in terms of both the extent of buffering from vehicles and vehicle volume.

Painted bicycle lanes and advisory bicycle lanes are perceived to be less safe than bicycle boulevards and buffered bicycle lanes. There is little difference between the perceived safety of painted bicycle lanes and residential collectors. Advisory bicycle lanes are perceived less safe than residential streets, where they may be implemented; although this may be a result of respondents being unfamiliar with advisory bicycle lanes as these facilities have not seen wide-spread adoption.

The increase in perceived safety of bi-directional protected bicycle lanes from more confident bicyclists to concerned bicyclists may be the result of concerned bicyclists' preference for protected facilities and simpler routing options versus a more confident bicyclist's awareness of the potential increase in vehicle turning movement conflicts due to bi-directional bicycle travel at intersections.

Children were asked where they like to ride their bicycle and why. Figure 3-2 shows that about 35% of children prefer to ride on the sidewalk. The main reasons provided for this are that they feel safe or they feel comfortable riding there. The second most common place where children like to ride their bicycle (nearly as commonly cited as riding on the sidewalk) is on the road, even if there is no special bicycle lane. In this case, however, safety was not identified as one of the main reasons but rather, they expressed that they find it comfortable to ride there, they can go fast, and they can ride with their friends. About 28% of children expressed that they prefer to ride their bicycles on the road but only on quiet streets. In this case, safety and comfort were about equally weighed for making this choice.

There are clear differences, however, between boys and girls with respect to where they like to ride their bicycle (shown in Figure 3-2). Over one-half of girls prefer to ride their bike on the sidewalk, compared to less than one-quarter of boys. Girls cited safety and comfort as the main reasons they selected this option. Boys prefer to ride their bicycle on the road, even if there is no special bicycle lane. Key reasons cited were comfort and being able to ride with friends. Nearly one-third of boys also indicated that they like riding their bicycle on quiet streets, compared to about one-quarter of girls.

Figure 3-1: Bicyclist perception of the safety of bicycle facilities

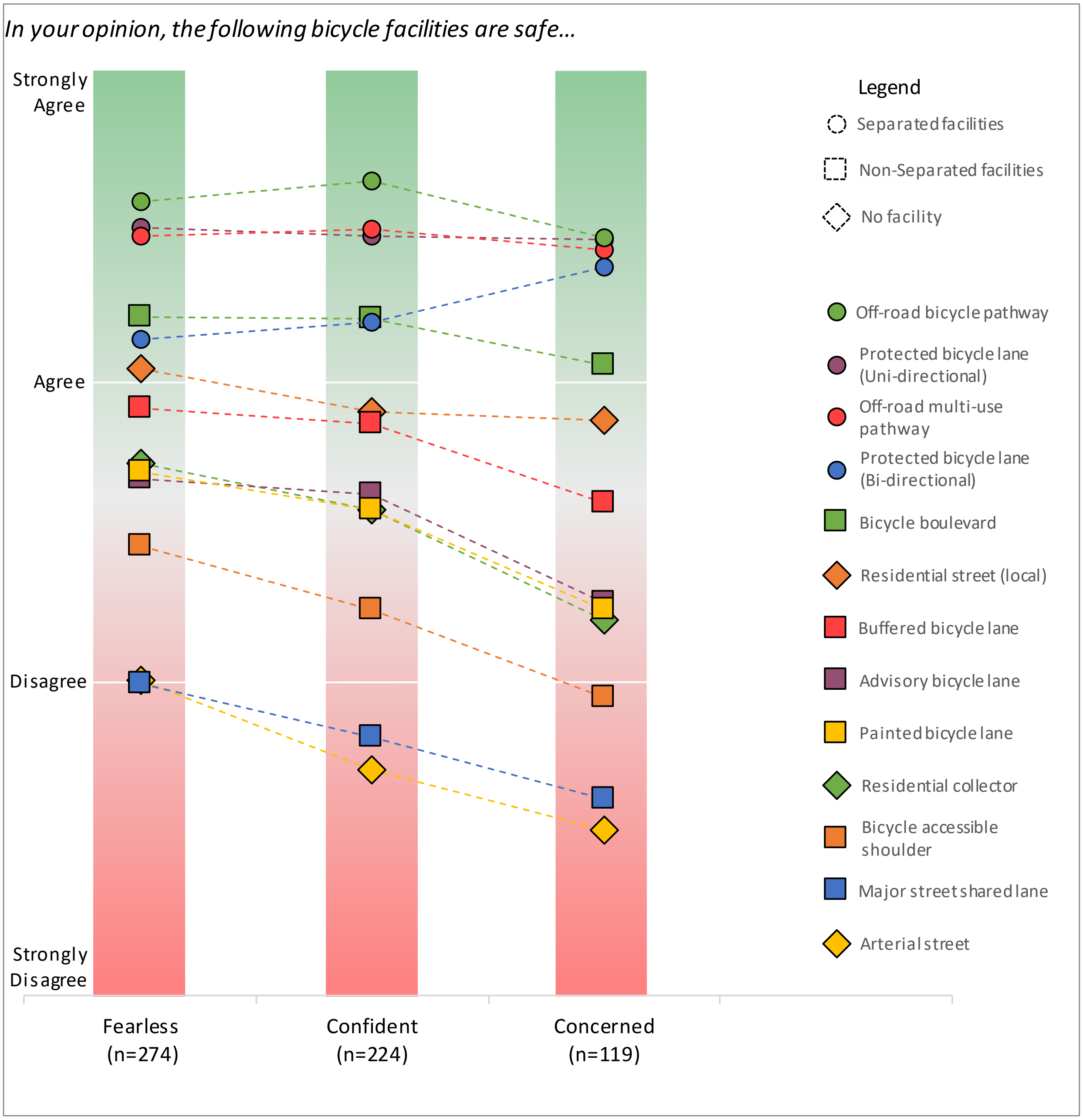
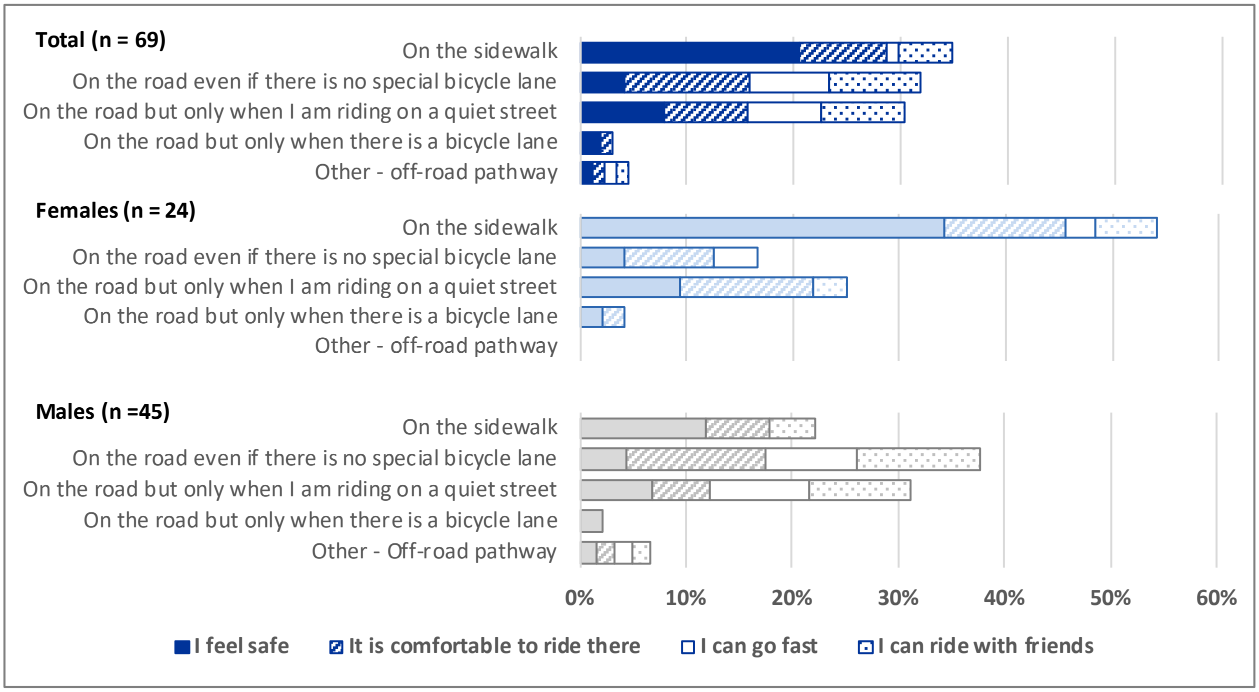


Figure 3-2: Childrens' preferred infrastructure for bicycle riding



3.2 Intersection treatments

The intersection treatments identified in Section 1.5.2 were included in this study based on their consideration in leading bicycle facility design guidelines and best practices identified by project steering committee members. This section presents results from the literature review and the end user survey on the observed and perceived safety of bicycle intersection treatments.

3.2.1 Literature review findings

Key findings from the literature regarding different intersection treatment type are discussed here. In general, there was a limited amount of quality literature to make strong conclusions on the observed safety of bicycle intersection treatments.

Protected intersection – The literature indicates that protected intersections with an island and/or green pavement marking show some improvements in driver performance with respect to the potential collision severity as measured by vehicle speeds in near and actual collisions (Hurwitz, Jannat, Warner, Monsere & Razmpa, 2015).

Bike box – The literature indicates that bike boxes are effective at stopping vehicles from encroaching in the bike box and reducing the number of bicycle-vehicle conflicts at signalized intersections (Dill, Monsere & McNeil, 2010). In addition, left-turning bicyclist compliance with traffic signals increases with the presence of a bike box (Casello, Fraser & Mereu, 2016). The effectiveness of bike boxes can be improved with the addition of colour, a protected bicycle signal phase, and a "No Right Turn on Red" sign. Current research relies on video observation for the collection of surrogate safety measures that include vehicle encroachment and traffic signal compliance.

The literature also indicates that bike boxes are perceived by bicyclists and motorists to increase the safety of signalized intersections (Dill et al., 2010; Wang et al., 2018). Bike boxes are also perceived to increase safety along roadways where bicyclists may need to wait to make a left-turn at an unsignalized intersection (Götschi, Castro, Deforth, Miranda-Moreno & Zangenehpour, 2018). When compared to two-stage turn boxes, bike boxes are perceived to be marginally safer (Wang et al., 2018).

Two-stage turn queue box - Few studies have been conducted regarding bicyclist safety using two-stage queue boxes. Two-stage turn queue boxes seem to encourage bicyclists to comply with traffic signals but are not as effective as bike boxes (Casello et al., 2017). Bicyclists also seem to perceive bike boxes to be safer than two-stage turn queue boxes (Wang et al., 2018).

Intersection crossing markings - The literature presents conflicting results regarding the safety performance of intersection crossing markings. Some literature indicates that intersection crossing markings improve collision avoidance of drivers at intersections with two bicycle crossings. A crossing with full green bike lanes and dotted white outline through the entire intersection is the most effective (Hurwitz, D. et al., 2015). However, intersections with more than one blue crossing marking (blue is used rather than green in some jurisdictions) increase total collisions and injuries of all modes; although increases in rear-end vehicle collisions and red-light running collisions played a primary role in the increase (Jensen, 2007).

The literature indicates that intersection crossing markings improve bicyclists' perception of safety. Research also indicates that in the mixing zones with turning vehicles that approach intersections, bicyclists perception of safety is more influenced by the number of turning vehicles rather than how vehicles and bicycles interact in these zones (Monsere, Foster, Dill & McNeil, 2015).

Cross-rides - Cross-rides are a relatively new treatment and few studies examine the bicycle safety impacts of cross-rides. Cross-rides seem to improve bicyclist safety at roundabouts (Sakshaug, Laureshyn, Svensson & Hydén, 2010).

Bend-in & Bend-out intersection approaches - There are few research studies available for bend-in intersection approaches. In Australia, bicyclists felt safer crossing roadways when they were required to yield to vehicle traffic rather than trusting that motorists would yield to bicyclists approaching from a bend-in and bend-out treatment (Ng et al., 2017).

Protected signal phases - Literature indicates that protected signal phases increase bicyclist safety at signalized intersections (Casello et al., 2016; Strauss, Miranda-Moreno & Morency, 2013). Alternatively, intersections with significantly longer green light cycles tend to have a lower risk of bicyclist injury (Burbridge, 2015).

The literature indicates that bicycle signals implemented for right-turns improve bicyclist perception of safety through intersections with right-turning vehicles (Abdul Rahimi, Kojima & Kubota, 2013) and that bicyclists seem to travel further distances to access protected bicycle signals phases (Winters, Teschke, Brauer & Fuller, 2016).

Gates, fencing, and bollards - In general, slowing bicyclist prior to vehicle conflict zones should improve reaction capabilities of both bicyclists and motorists to avoid collisions. However, there was no research reviewed on bicyclist safety outcomes of gates, fencing and bollards.

Table 3-2 summarizes the literature findings by general safety outcome for collision risk, collision severity, and perceived safety.

Table 3-2: Safety outcomes of bicycle intersection treatment types based on published research

Intersection treatment type	Collision risk	Collision severity	Perceived safety
Protected intersection		○	
Bike box	●		○
Two-stage turn queue box	○		○
Intersection crossing markings	○, □*		○
Cross-rides	○		
Bend-in, bend-out approach			
Protected signal phase	○		
Gates, fencing, bollards			

● Well supported positive outcome
○ General positive outcome
□ General negative outcome
■ Well supported negative outcome
** Various results*
Blank cells indicate limited research available

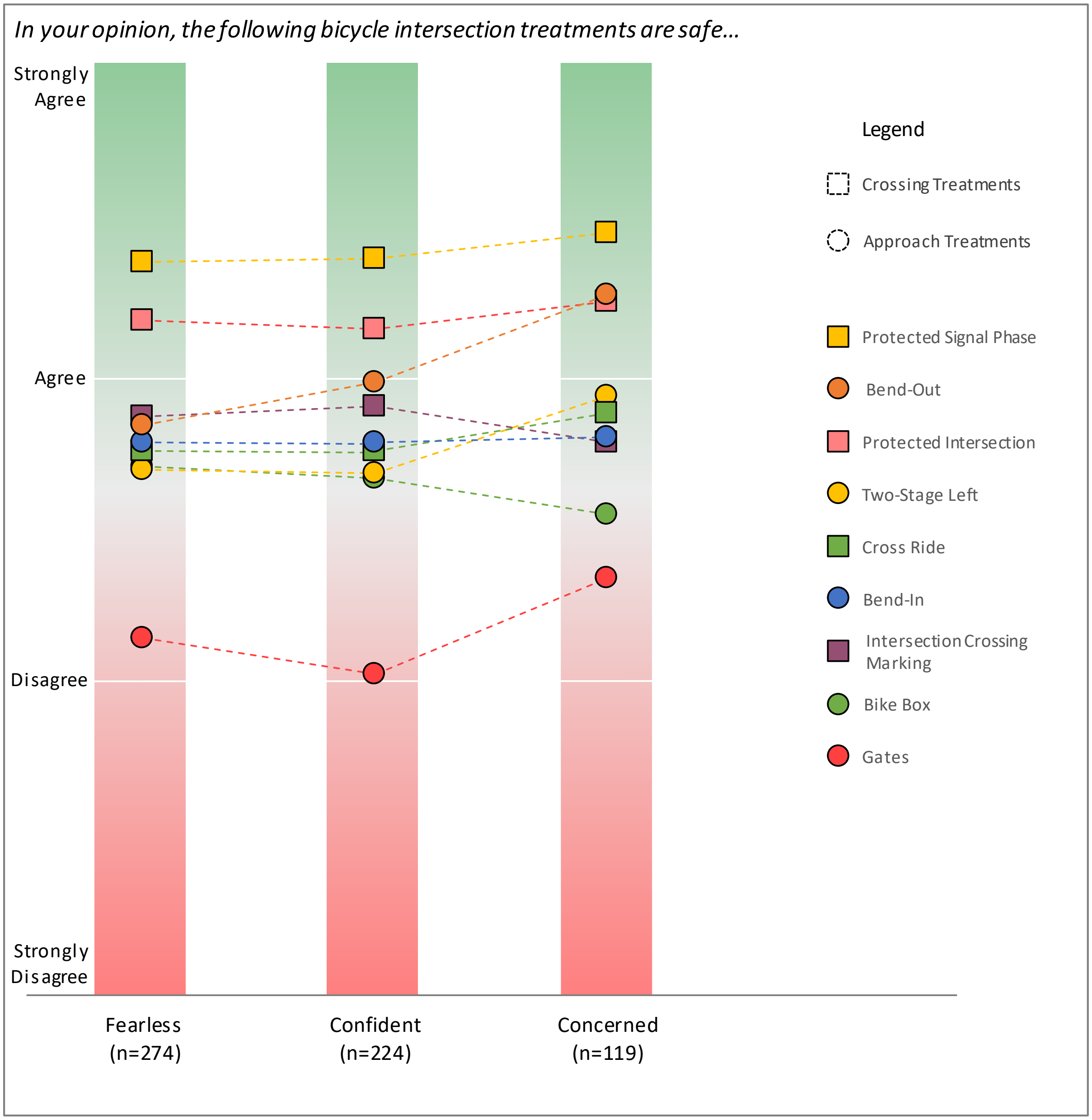
3.2.2 End user survey results

Figure 3-3 shows how respondents perceive the safety of bicycle intersection treatments based on their self-identified bicyclist type. All bicycle intersection treatments, except for gates, are perceived to be safe by respondents. Protected signal phases are perceived to be the safest followed by protected intersections. The perception of safety by fearless bicyclists is relatively consistent with confident bicyclists but not with concerned bicyclists.

In general, bend-out approaches are perceived to be safer by concerned bicyclists than fearless and confident bicyclists. This may be attributed to the relatively small sample size of all bicyclist types that have used bend-out approach treatments, which may result in a more volatile result.

Bike boxes and two-stage left turn queues are both implemented to position bicyclists in front of vehicles at intersections to ensure that they are visible prior to entering conflict zones in the intersection. It is conceivable that these treatments may not be preferred by concerned bicyclists who prefer not to ride in vehicle lanes. However, while concerned bicyclists perceive bike boxes to be less safe than more confident bicyclists but they perceive two-stage lefts to be safer than more confident bicyclists. Further analysis of survey results reveals that two-stage lefts and bike boxes are perceived to be equally as safe when considering only concerned bicyclists who have experience bicycling on both treatments.

Figure 3-3: Bicyclist perception of the safety of bicycle intersection treatments



Because protected bicycle facilities may be designed to carry bi-directional bicycle traffic on one side of the street, resulting in a unique safety concern at intersections given that motorists may not be prepared to check for bicyclists travelling in both directions on one side of the street, survey respondents were asked to share their views regarding bicycling through intersections when travelling on one-way and two-way protected bicycle lanes along one-way and two-way roadways and on contra-flow bicycle facilities (i.e. in the opposite direction of vehicle travel). The various intersection configurations considered in this question are illustrated in Figure 3-4.

Figure 3-4: Configurations of protected bicycle facilities at intersections

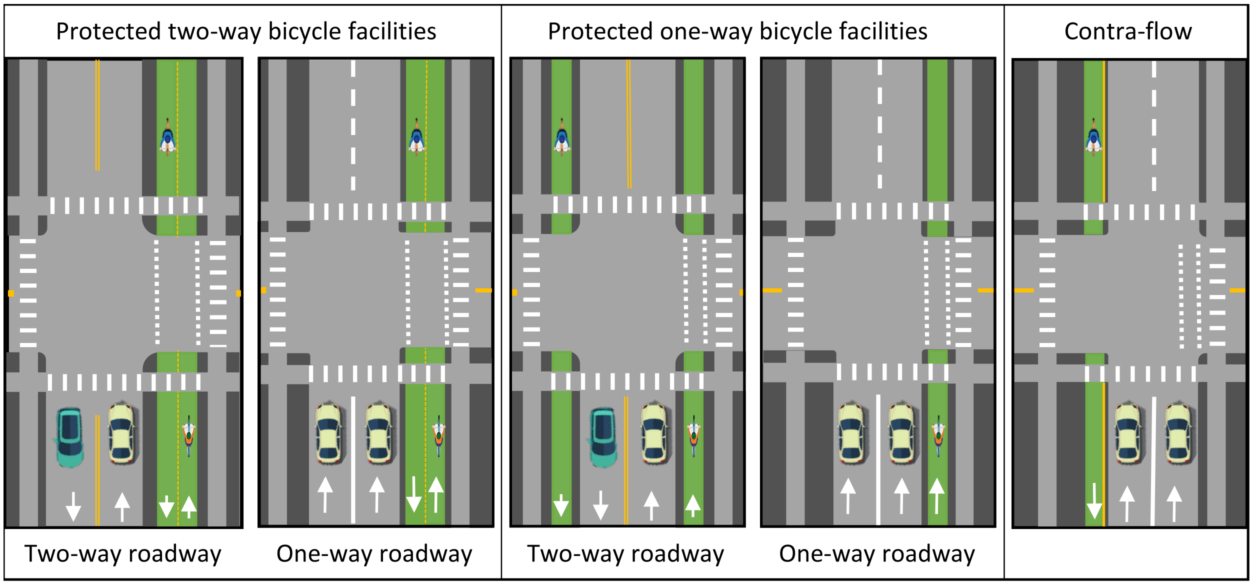


Figure 3-5 shows how respondents perceive the safety of bicycling through intersections using the various configurations of protected bicycle facilities and roadways. Results indicate that fearless and confident bicyclists perceive one-way bicycle facilities to be safer than two-way bicycle facilities at intersections regardless of whether they are implemented along one-way or two-way roadways. Concerned bicyclists perceive the opposite, that two-way bicycle facilities are safer than one-way bicycle facilities at intersections. Contra-flow protected bicycle lanes are perceived to be the least safe configuration at intersections by all types of bicyclists.

Children were also asked how they feel when approaching a busy, signalized intersection. As Figure 3-6 shows, most children feel somewhat safe (one-third of children) when approaching this type of intersection. Approximately one-half feel somewhat unsafe or very unsafe, and 16% feel very safe.

The approach children take when they arrive at an intersection depends on whether it is a busy, signalized intersection or a quiet, stop-controlled intersection. As Figure 3-7 illustrates, most children get off their bicycle and walk across busy signalized intersections, while stop-controlled intersections are treated differently. At these locations, children reported to just slow down and ride through the intersection if it was safe to do so. The figure also shows that over 20% of children responding to the survey indicated that they only slow down and ride through busy, signalized intersections if it is safe to do so. The ‘other’ behaviour cited by children when approaching an intersection was to follow the signals and ride through when it is safe to do so.

Figure 3-5: Bicyclist perception of safety cycling through intersections from protected bicycle facilities

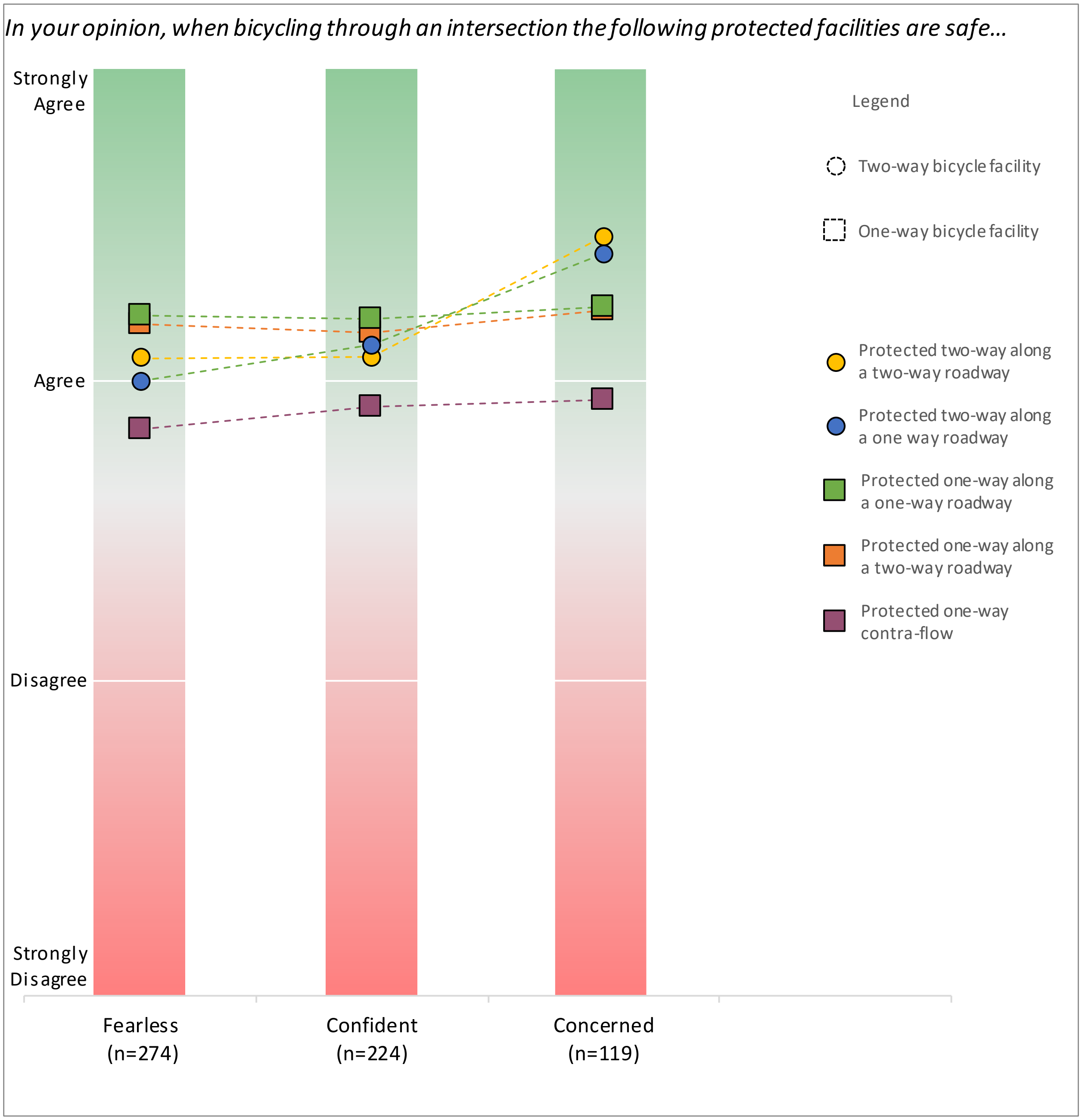


Figure 3-6: Perception of safety at large signalized intersections

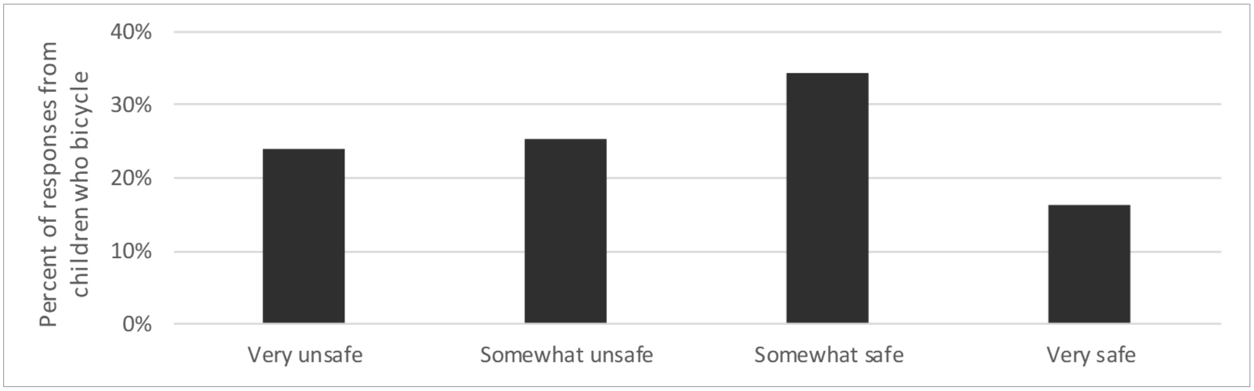
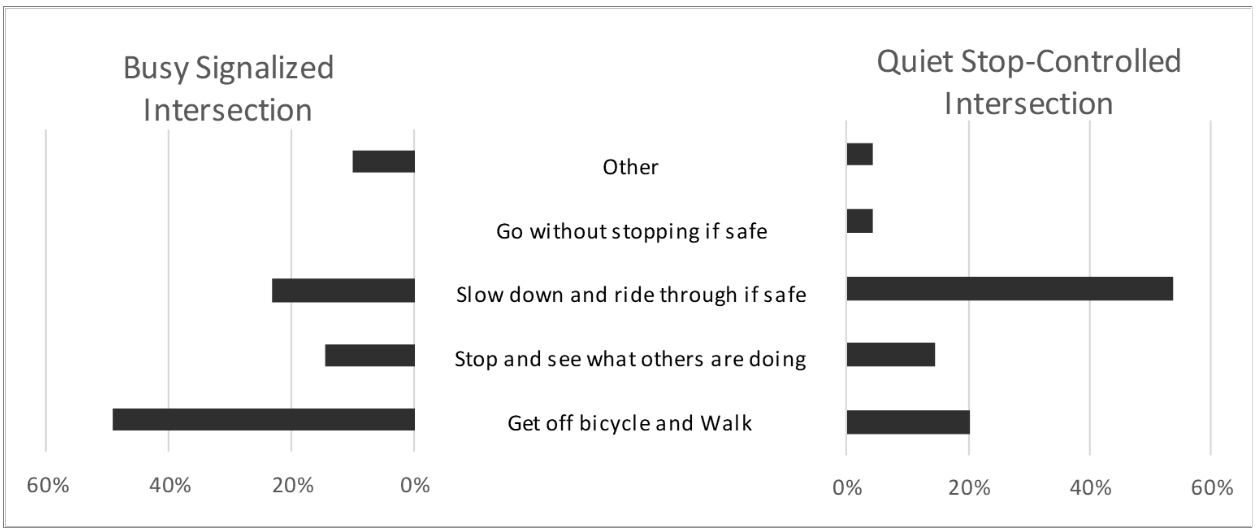


Figure 3-7: Children's behaviour by intersection type



3.3 Factors influencing bicycle safety

The literature review and end user survey investigated the influence of factors other than bicycle infrastructure that may affect observed and perceived safety.

3.3.1 Literature review findings

The following factors were identified in the literature as playing a significant role in observed and perceived bicyclist safety:

Vehicle speed – The literature indicates that higher vehicle speeds increase the risk of bicyclist injury and injury severity in the event of a collision along roadways and at intersections (Bíl, Bílová & Müller, 2010; Chen & Shen, 2016; Cripton et al., 2015; Gårder, Leden & Pulkkinen, 1998; Harris et al., 2013). Specifically, vehicle speeds less than 30 km/h significantly reduce bicyclist risk of injury at intersections. In addition, bicyclists prefer to travel by bicycle along routes with lower vehicle speeds (Harris et al., 2013). Although one source indicates there is no significant relationship between posted speed limit and bicyclists perception of safety at intersections (Wang et al., 2018).

Vehicular traffic volume - Findings reveal that as vehicular traffic volumes increase collision severity decreases (Caviedes, Alvaro; Figliozzi, 2018) and that collision frequency decreases when segments and intersections are not considered separately (Kaplan & Giacomo Prato, 2015; Osama & Sayed, 2016). However, at intersections, collision frequency increases with an increase in vehicle traffic volumes. In addition, bicyclists' perception of safety decreases with an increase in vehicle traffic volume (Nordback, Marshall & Janson, 2014; Oh, Jun, Kim & Kim, 2008).

Bicycle traffic volume - It is well documented that bicyclist safety risk decreases with higher bicyclist traffic volumes (Elvik, 2009; Kaplan & Giacomo Prato, 2015; Nordback et al., 2014; Osama & Sayed, 2016; Pucher, Buehler & Seinen, 2011; Strauss et al., 2013).

Road classification - Jurisdictions classify their roadways by their function into expressways, major arterials, minor arterials, collectors and local roads to represent various roadway characteristics that include vehicular volume, posted speed limit, number of vehicle lanes, presence of parking, presence of a median, and number of intersections. While each jurisdiction defines their roadways classifications differently, in general the intention of each classification is similar where lower functional classes (e.g. local roads) represent quiet streets with low vehicle volumes and speeds and higher functional classes (e.g. expressways) represent busy roadways with high vehicle volumes and speeds. In the absence of safety research on specific roadway characteristics, research on the safety impacts of roadway functional classifications can provide a general understanding of safety. Overall, the literature indicates that the risk of bicyclist injury increases as roadway functional classification increases (Aguilar & Hamdar, 2018; Harris et al., 2013; Osama & Sayed, 2016; Teschke et al., 2012).

Presence of vehicle parking - The presence of vehicle parking along a bicycle route has been found to increase the risk of collisions involving bicyclists (Teschke et al., 2012). One reason for the increase in collisions is due to drivers opening their door into the bicyclists travel path (termed "dooring") causing the bicyclist to swerve into the adjacent vehicle lane or collide with the vehicle door. Research suggests that cycling guidelines do not adequately account for the door zone and as a result, bicyclists travelling in painted bicycle lanes have been found to travel too closely to parked vehicles (Schimek, 2017). More recently, Ottawa has tested the addition of a pavement marking that highlights the dooring zone alongside central-sharrows. Results indicate that the use of dooring-zone markings causes bicyclists to travel further from the parking lane edge line (i.e. close to the central-sharrow) and motor vehicles were less likely to pass a bicyclist (Kassim, Ismail & McGuire, 2019).

Some literature indicates that the presence of vehicle parking along bicycle facilities reduces bicyclists perception of safety (Chataway et al., 2014; Winters & Teschke, 2010).

Roadway width - For every 10 ft (3 m) of curb-to-curb width, the risk of bicycle-vehicle collision increases (Hamann & Peek-Asa, 2013). In other words, the wider the road the greater the risk of a bicycle-vehicle collision.

Number of vehicle travel lanes – While the number of marked traffic lanes is not significantly associated with an increase in bicyclist injury risk compared to non-marked traffic lanes (Teschke et al., 2012), an increase in the number of vehicle travel lanes is associated with a decrease in bicyclists perception of safety (Chataway et al., 2014; Wang et al., 2018).

Roadway curb type – Compared to mountable curbs, non-mountable curbs presented statistically significant higher odds of a bicyclist being in a collision with a motor vehicle and that collision resulting in a severe injury (Romonow et al., 2012).

Bicycle facility surface type - For off-street paths, paved routes were preferred over unpaved routes, especially among regular bicyclists (Winters & Teschke, 2010). In Stockholm, Sweden, the second most frequent safety problem was found to be attributable to the type of surface of the road or bicycle-lane/path; the first was facility design (Gustafsson & Archer, 2013).

Bicycle facility surface condition - The risk of experiencing a critical event is significantly higher when the road surface is poorly maintained and in proximity to intersections (Dozza & Werneke, 2014).

Bicycle facility grade - Downhill sloped bicycle facilities have been found to both increase the risk of a bicyclist collision (Teschke et al., 2012) and the chances of the bicyclists requiring ambulance transportation to the hospital (Cripton et al., 2015).

Presence of trucks – The presence of trucks has been found to increase the perceived safety risk of bicyclists which further increases as truck speed increases (Llorca, Angel-Domenech, Agustin-Gomez, & Garcia, 2017). It is generally understood that the aerodynamic forces exerted on bicyclists by passing vehicles are a function of truck type/size, truck speed, and lateral separation distance between the bicyclist and truck. The aerodynamic force acts laterally on the bicyclist; initially pushing the bicyclist away from the truck and then pulling the bicyclist towards the truck in the slipstream or wake. The rapid change between the heavier push and light pull may cause the bicyclist to lose their balance (Walton, Dravitzki, Cleland, Thomas, & Jackett, 2005). Recent research has found that the aerodynamic forces of a full-size pick-up truck are still present beyond a lateral separation of 3 m (Lubitz & Rubie, 2018). The Ministry of Transportation of Ontario suggests that additional buffer width or physical separation should be considered for bicycle facilities when there are more than 30 trucks or buses per hour in the curb lane (MTO, 2014). In addition, the FHWA recognizes that trucks have larger blind-spots and there is a higher potential that bicyclists may not been seen (FHWA, 2019).

Presence of transit - The presence of bus stops increases bicyclist collision frequency (Chaney & Kim, 2014; Strauss et al., 2013) and decreases bicyclist safety perception (Gustafsson & Archer, 2013). Further, the presence of streetcar or train tracks is significantly associated with increased risk of bicyclist injury (Teschke et al., 2012).

Street lighting - Street lighting has been found to improve bicyclist safety (Chen & Shen, 2016; Reynolds, Harris, Teschke, Cripton & Winters, 2009).

Table 3-3 summarizes the results from the literature review by the general safety outcome for collision risk, collision severity and perceived safety.

Table 3-3: Safety outcomes of bicycle safety factors from literature

Bicycle safety factors	Collision risk	Collision severity	Perceived safety
Low vehicle speed	●	●	○
Low vehicle traffic volume	○ ☐	☐	○
High bicycle traffic volume	●		●
Higher road classification	■		
Presence of vehicle parking	☐		☐
Wider roadway width	☐		
Higher number of vehicle travel lanes	△		☐
Mountable curbs	○		
Paved bicycle facility surface			○
Poor bicycle facility surface condition	■		
Downhill sloped bicycle facilities	■		
Presence of trucks	☐		☐
Presence of transit	☐		☐
Presence of street lighting	○		

● Well supported positive outcome
○ General positive outcome
△ Neutral outcome
☐ General negative outcome
■ Well supported negative outcome
Blank cells indicate limited research available

3.3.2 End user survey results

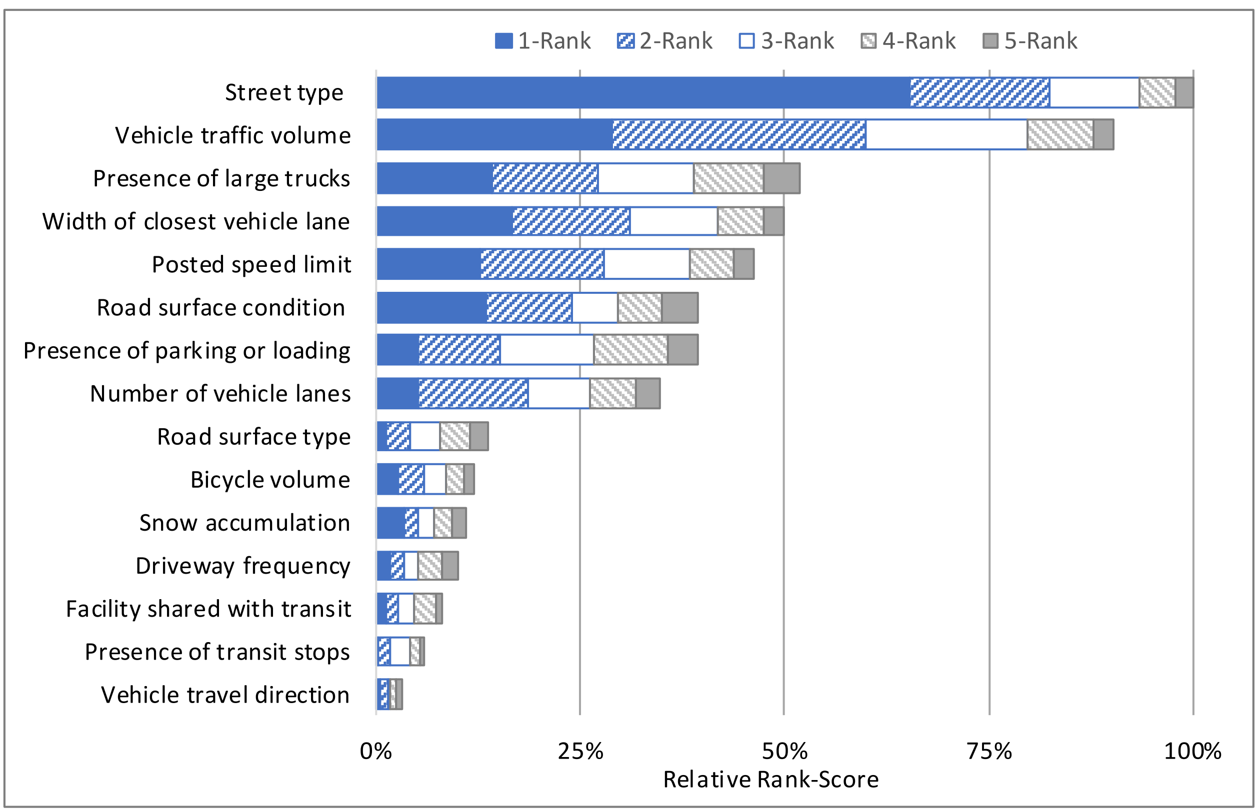
End user survey respondents were asked to rank the top five factors that influence their feeling of safety while bicycling from a list of 13 factors. The relative rank of factors influencing respondents' perception of safe bicycling is shown in Figure 3-8.

Results show that street type and vehicle traffic volume, which are closely related factors, are most significant in respondents' perception of safety while bicycling. After street type and vehicle traffic flow, a second group of factors with similar significance include the presence of large trucks, width of the closest vehicle travel lane, posted speed limit, and road surface condition. These are followed by the less significant factors which are presence of vehicle parking or loading along the roadway, and number of vehicle travel lanes. Posted speed limit and number of vehicle travel lanes are often used to define street type. The presence of large trucks, width of closest vehicle lane, posted speed limit and presence of parking and loading are all related to the presence of vehicles but differ based on vehicle size (large trucks vs. vehicle) and vehicle speed (moving vs. stationary).

Vehicular traffic volume, posted speed limit, presence of parking or loading, and number of vehicle travel lanes are common factors that influence bicyclist safety perception and are often used to define street type or roadway classification. This underscores the importance of well-defined street types and the potential impact of diverse street types definitions among jurisdictions when applying a bicycle facility implementation decision tool nationwide. The high rank-score of vehicle traffic volumes suggests that, of the factors that define street type, vehicle traffic volume has the largest influence on bicyclists' perception of safety. As a result, the vehicle traffic volume ranges that define street type should be considered with care and may need to be considered in finer detail when deciding which bicycle facilities to implement.

The remaining seven factors all scored less than 15% compared to street type, the highest-ranking factor. These lower scoring factors include road surface condition, bicycle volume, snow accumulation, driveway frequency, facility shared with transit, presence of transit stops, and vehicle direction of travel, although they were all ranked first by several respondents. The low score of transit related factors is not supported by the high score of the presence of large trucks, given that transit vehicles can be considered as large vehicles. Snow accumulation was identified as rank-1 the most often amongst the bottom seven factors; there is a potential bias reducing the rank-score of the snow accumulation factor because only about 50% of respondents indicated that they bicycle in winter months and may have only considered factors that influence their perception of safety in other seasons.

Figure 3-8: Relative rank-score of factors influencing bicyclist perception of safety

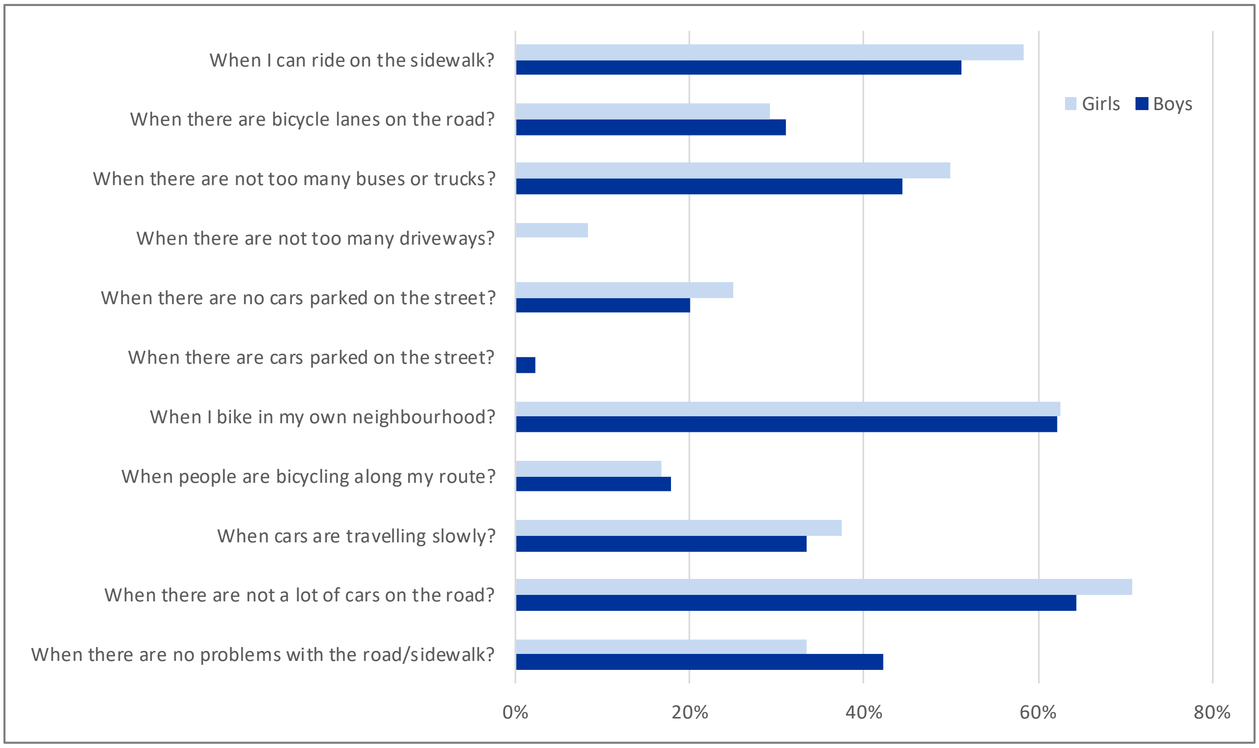


The youth survey asked about the most important factors that make children feel safe while bicycling. Figure 3-9 shows that, regardless of gender, the issues that were most commonly cited by children as inducing a feeling of safety when riding a bicycle are:

- Low traffic volumes
- Riding in their own neighbourhood
- Riding on the sidewalk
- Low bus and truck volumes

In all cases, except for riding in their own neighbourhood, more girls than boys identified those as the key issues that make them feel safe when riding a bicycle. Two differences between boys and girls (although in very low numbers) is that boys feel safer when there are parked vehicles on the road, while girls feel safer where there are not too many driveways.

Figure 3-9: Factors that make children feel safe when riding a bicycle



4. Bicycle infrastructure implementation in Canada

This chapter presents results from the jurisdictional survey about the state-of-the-practice in Canada regarding the following:

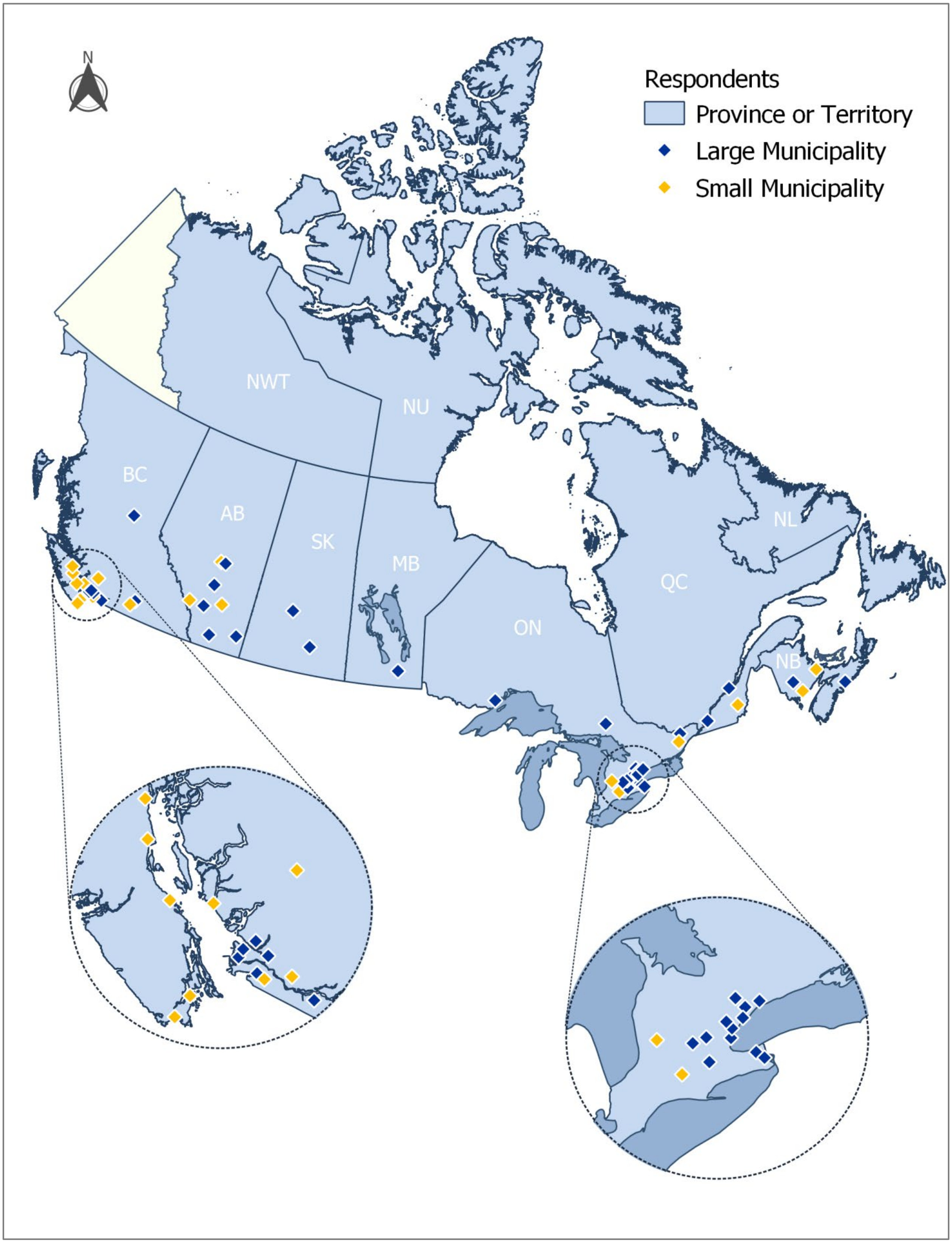
- Commonly used bicycle design guidelines
- The extent of implementation of bicycle facilities
- The extent of implementation of bicycle intersection treatments
- Bicycle safety data collection and evaluation
- Bicycle infrastructure selection practice

Details about this survey are included in Appendix C. Table 4-1 shows the responding jurisdictions by type and Figure 4-1 illustrates the location of these jurisdictions.

Table 4-1: Jurisdictions responding to state-of-the-practice survey

Large municipality (39)		Small municipality (19)	Province and territory (11)
Brampton	North Vancouver	Campbell River	Alberta
Brantford	Oakville	Canmore	British Columbia
Calgary	Ottawa	Colwood	Manitoba
Chilliwack	Peel	Courtenay	New Brunswick
Coquitlam	Prince George	Dieppe	Newfoundland and Labrador
Durham	Québec City	Drumheller	Northwest Territories
Edmonton	Red Deer	Grand Bay-Westfield	Nova Scotia
Fredericton	Regina	Huron County	Nunavut
Greater Sudbury	Richmond	Ingersoll	Ontario
Guelph	Saskatoon	Lambton	Québec
Halifax	St. Catharines	Langley	Saskatchewan
Kelowna	Strathcona	Mission	
Lethbridge	Surrey	North Saanich	
Markham	Thunder Bay	Parksville	
Medicine Hat	Toronto	Sechelt	
Mississauga	TransLink	Smiths Falls	
Montréal	Vancouver	Spruce Grove	
Newmarket	Waterloo	Summerland	
Niagara Falls	Whitby	Whistler	
	Winnipeg		

Figure 4-1: Location of responding jurisdictions



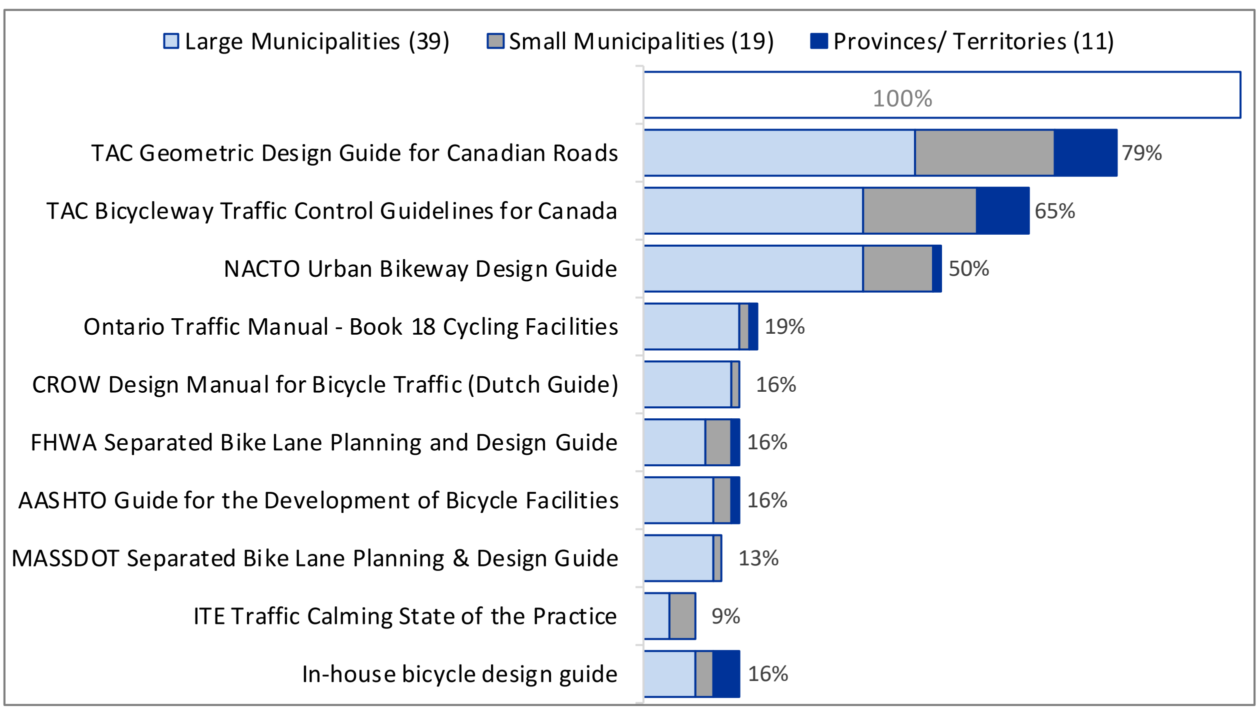
4.1 Use of bicycle infrastructure design guides

There are many guidelines available to practitioners for guidance on bicycle infrastructure design. While the first North American bicycle infrastructure design guide was released in 1999 (AASHTO's *Guide for the Development of Bicycle Facilities*) it was not until 2010 that facilities other than off-road pathways and painted bike lanes were included in the first edition of the NACTO *Urban Bikeway Design Guide*. Since then, there have been many bicycle design guides published by various North American groups. However, as more is understood about bicycle infrastructure safety and bicyclists' perception of safety, the design standards and guidelines continue to evolve and vary from guide to guide.

Figure 4-2 shows the proportion of respondents that use different bicycle design guidelines by jurisdiction type. As the figure shows, the TAC *Geometric Design Guide for Canadian Roads* (GDG) (TAC, 2017) is the most commonly used document by jurisdictions across Canada with over three quarters (78%) of respondents indicating that they use it for bicycle facility design. The latest edition of the GDG was produced in 2017 and was the first to include a section on bicycle infrastructure. The second most commonly used guide is TAC's *Bikeway Traffic Control Guidelines for Canada* (TAC, 2012), used by 65% of jurisdictions. The NACTO *Urban Bikeway Design Guide* (NACTO, 2014) was a common choice among respondents from large municipalities (64%) and small municipalities (42%).

Other resources stated by jurisdictions are British Columbia's *Bicycle Traffic Control Guidelines*, BC MOTI Bicycle Policy & Valley Trail design guidelines, TransLink Wayfinding Guidelines, Alberta's *Highway Geometric Design Guide*, and Vélo Québec's *Planning and Design for Pedestrians and Cyclists*.

Figure 4-2: Extent of use of common bicycle infrastructure design guidelines



4.2 Extent of implementation of bicycle facilities

The extent of use of different types of bicycle facilities is summarized in Table 4-2 by jurisdiction type. The table indicates that off-road multi-use pathways are the most common facilities implemented (determined by the addition of occasional and frequent responses) in large municipalities (100%) and small municipalities (83%), followed by painted bicycle lanes (92% of large and 78% of small municipalities). The most common facility implemented by provinces is the bike accessible shoulder (91%). Off-road multi-use pathways were the second most commonly implemented facility in provinces with 60% indicating their use. Other key findings from Table 4-2 are:

- Overall, the most commonly implemented facilities from all respondents are: off-road multi-use pathway (90% of respondents) and painted bicycle lane (82% of respondents). When it comes to frequency of implementation, jurisdictions indicated that they *frequently* implement the following types of facilities: off-road multi-use pathways (46%), painted bicycle lanes (33%) and bicycle accessible shoulders (27%). Protected bicycle lanes were identified as a *frequently* implemented facility by 12% of the jurisdictions.
- Only 11% of all respondents indicated the use of advisory bicycle lanes which may be due to it being a relatively new facility that few jurisdictions are currently piloting and assessing their performance.
- 18% of large municipalities indicated they *frequently* implement protected bicycle lanes; however, 49% have *never* implemented them.
- Respondents were also asked to indicate how frequently they implement their one-way and two-way protected and buffered facilities alongside one-way and two-way roadways. This distinction is important due to the potential safety concerns associated with bicycles and vehicles travelling in different directions or making unexpected movements at intersections. The survey found that:
- Overall one-way bicycle facilities (71% of large municipalities) are more common than two-way bicycle facilities (46% of large municipalities).
- Along one-way roadways, contra-flow one-way bicycle facilities are more common (28% of large municipalities) than two-way protected bicycle facilities (21% of large municipalities) and two-way buffered bicycle facilities (13% of large municipalities).

Table 4-2: Extent of implementation of various bicycle facility types

Large Municipalities	Never	Occasionally	Frequently	Extent of Use*
Off-Road Multi-Use Pathway	0%	36%	64%	100%
Protected Bicycle Lane	49%	33%	18%	51%
Buffered Bicycle Lane	41%	49%	10%	59%
Painted Bicycle Lane	8%	49%	44%	92%
Bike Accessible Shoulder	33%	44%	23%	67%
Major Street Shared Lane	32%	55%	13%	68%
Bicycle Boulevard	44%	49%	8%	56%
Advisory Bicycle Lane	88%	9%	3%	12%
Small Municipalities	**Never**	**Occasionally**	**Frequently**	**Extent of Use***
Off-Road Multi-Use Pathway	17%	50%	33%	83%
Protected Bicycle Lane	63%	32%	5%	37%
Buffered Bicycle Lane	63%	37%	0%	37%
Painted Bicycle Lane	22%	50%	28%	78%
Bike Accessible Shoulder	29%	47%	24%	71%
Major Street Shared Lane	59%	35%	6%	41%
Bicycle Boulevard	88%	6%	6%	12%
Advisory Bicycle Lane	94%	0%	6%	6%
Provinces/Territories	**Never**	**Occasionally**	**Frequently**	**Extent of Use***
Off-Road Multi-Use Pathway	40%	60%	0%	60%
Protected Bicycle Lane	64%	36%	0%	36%
Buffered Bicycle Lane	73%	27%	0%	27%
Painted Bicycle Lane	56%	44%	0%	44%
Bike Accessible Shoulder	9%	45%	45%	91%
Major Street Shared Lane	64%	36%	0%	36%
Bicycle Boulevard	100%	0%	0%	0%
Advisory Bicycle Lane	82%	18%	0%	18%
Total	**Never**	**Occasionally**	**Frequently**	**Extent of Use***
Off-Road Multi-Use Pathway	10%	43%	46%	90%
Protected Bicycle Lane	55%	33%	12%	45%
Buffered Bicycle Lane	52%	42%	6%	48%
Painted Bicycle Lane	18%	48%	33%	82%
Bike Accessible Shoulder	28%	45%	27%	72%
Major Street Shared Lane	44%	47%	9%	56%
Bicycle Boulevard	64%	30%	6%	36%
Advisory Bicycle Lane	89%	8%	3%	11%

Extent of use proportion is calculated as the number of responses indicating 'occasionally' and 'frequently', divided by the total number of responses (the total number of responses may vary due to skipped questions).

4.3 Extent of implementation of bicycle intersection treatments

The extent of use of different types of bicycle intersection treatments is summarized in Table 4-3 by jurisdiction type. The table indicates that the most common intersection treatments implemented in large municipalities are: gates, fencing and bollards (used by 63% of large municipalities), cross-rides (used by 47% of large municipalities), bike boxes (used by 39% of large municipalities), and intersection crossing markings (used by 39% of large municipalities). The most common intersection treatments implemented in small municipalities are: gates, fencing and bollards (used by 47% of small municipalities), bend-in intersection approaches (used by 32% of small municipalities), and intersection crossing markings (used by 26% of small municipalities).

Other key findings from Table 4-3 are:

- The least common intersection treatment type by large municipalities is the bend-out intersection approach along two-way roadways (10%).
- Cross ride treatments are common among large municipalities (49%), however few others use them (11% of small municipalities and 9% of provinces).
- The bend-in intersection approach treatment is the second most common used in provinces/territories (18%) and in small municipalities (32%)

Table 4-3: Extent of implementation of various intersection treatment types

Intersection Treatment	Large Municipalities (39)	Small Municipalities (19)	Provinces/ Territories (11)
Intersection crossing marking	41%	26%	27%
Bike box	41%	5%	9%
Two stage turn Queue Box	28%	0%	9%
Cross Rides	49%	11%	9%
Bend-in Intersection approach	36%	32%	18%
Bend-out intersection approach	26%	5%	9%
Protected Signal Phase (Bike Signal)	31%	11%	9%
Gates,Fencing, and Bollards	62%	47%	9%

4.4 Data collection and evaluation

At a minimum, evaluation of bicycle infrastructure safety requires bicycle exposure (e.g. bicycle volume data) and bicycle safety data (e.g. hospitalization records, collision reports and conflicts). Survey findings on bicycle exposure data, bicycle safety data, and bicycle safety evaluation are presented in this section.

4.4.1 Bicycle exposure data

While most jurisdictions have scheduled motorized traffic monitoring programs that are used to systematically collect vehicular traffic data throughout their entire roadway network, few have similar resources allocated to the collection of bicycle volume data. Table 4-4 shows a summary of findings regarding exposure data.

Table 4-4: Bicycle volume data collection method

Bicycle data source	Large municipalities (39)	Small municipalities (19)	Provinces/ territories (11)
Surveys and counts conducted as needed	90% (35)	74% (14)	55% (6)
Volumes are determined from a bicycling demand model or other forms of latent bicycling demand projections	3% (1)	42% (8)	9% (1)
Volumes are available from a scheduled bicycling or active transport monitoring program	26% (10)	11% (2)	9% (1)
Bicyclists counted as part of intersection turning movement counts	72% (28)	5% (1)	36% (4)
Other	15% (6)	5% (1)	0

Other: All 7 municipalities that responded "other" indicated that they use automated bicycle counting devices.

Table 4-4 shows the following:

- The most common bicycle volume data source for all jurisdiction types is conducting surveys and counts as needed or requested (90% of large municipalities, 74% of small municipalities, 55% of provinces/territories). In these cases, these jurisdictions do not necessarily have a regular bicycle counting program in place.
- Almost one-quarter (26%) of large municipalities indicated having implemented a scheduled monitoring program that includes bicycles. However, the most common way of obtaining bicycle volume data is still either through ad-hoc counts, as needed (as above), or as part of intersection turning movement counts (reported by 72% of large municipalities).
- The second most common method for provinces/territories to obtain bicycle volume data as part of intersection turning movement counts (36% of provinces/territories).

The type of counting technology used provides an indication of the count duration and accuracy which corresponds to the quality of the bicycle volume data. For example, manual counting provides high-accuracy but is only collected for short-durations. Alternatively, infrared sensors can collect volume data for long durations but have a reduced accuracy. Key findings from the survey are:

- Manual counters are the most common choice for measuring bicycling exposure for all jurisdiction types (79% of large municipalities, 68% of small municipalities, 55% of provinces/territories).
- Large municipalities also use video detection, inductive loops and infrared sensors in addition to manual counters.
- Provinces/territories do not typically rely on emerging technology like infrared sensors and mobile crowd sourcing apps for bicycle counting.

4.4.2 Bicycle safety data

Traditionally, safety data comprises collision data from police traffic collision reports that result in fatalities, injuries, or a specific amount of property damage. As a result, bicycle collisions that do not involve a motor vehicle are rarely reported to the police. This has prompted jurisdictions to find alternative sources of bicycle safety data. Alternative sources include hospitalization records, public safety perception, manual observation (e.g. bicycle safety reviews), and video conflict analysis which quantifies near-miss conflicts as a surrogate for safety. Table 4-5 summarizes results regarding the different types of bicycle safety data used by different jurisdictions. The table shows the following:

- The lack of good bicycle safety data was cited as a barrier to evaluating safety performance by 41% of large municipalities, 53% of small municipalities, and 55% of provinces/territories.
- Bicycle collision data from police records was the most commonly identified source of bicycle safety data by all jurisdictions (87% of large municipalities, 47% of small municipalities, 55% of provinces/territories).
- Bicycle collision data from insurance records was identified as a data source by 47% of small municipalities but only 28% of large municipalities and 9% of provinces/territories.
- Provinces and territories rely mainly on collision data from police reports.

Table 4-5: Bicycle safety data used for safety performance measurement

Bicycle safety data source	Large municipalities (39)	Small municipalities (19)	Provinces / territories (11)
Bicycle collision data from police records	87% (35)	47% (9)	55% (6)
Bicycle collision data from insurance records	28% (11)	47% (9)	9% (1)
Bicycle collision data from hospital records	8% (3)	0	9% (1)
Video conflict data	17% (7)	0	0
Public feedback	56% (22)	47% (9)	18% (2)
Manual observations	51% (20)	11% (2)	9% (1)
Lack of data is a barrier to evaluating the safety performance of bike facilities	41% (16)	53% (10)	55% (6)
Other data sources	8% (3)	0	0

Other: All identified bikemaps.org as a source of bicycle safety data.
The number in brackets refers to the total number of respondents

4.4.3 Bicycle infrastructure safety performance evaluation

A critical component to providing safe accommodation for bicyclists is the ability to objectively evaluate the safety performance of bicycle infrastructure after implementation. Ideally, there would be enough high-quality data available to develop safety performance functions or collision modification factors for various bicycling facilities and intersection treatments. However, development of this information requires robust data for a few years, which is rarely available for bicycle infrastructure. The survey sought to understand the types of studies that are being completed to evaluate the safety performance of bicycle infrastructure and the following was found:

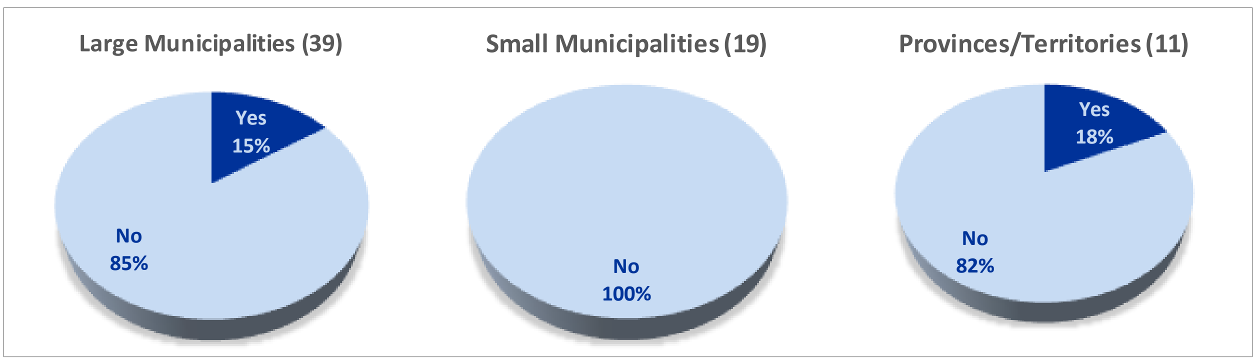
- Overall, 44% of all respondents indicated that they were unaware of any evaluations or studies conducted in their local jurisdiction regarding the safety performance of bicycle facilities (35% of large municipalities, 58% of small municipalities, 55% of provinces/territories). In addition, another 10% of respondents did not answer the question.

- Over one-third (36%) of provinces/territories indicated that they have developed warrants for deciding whether to build a cycling facility.
- The most common studies/evaluations completed by large municipalities are studies on the appropriate application of different types of bicycle facilities (42%), safety evaluations like bicycle road safety audits (26%), and before and after studies (26%).

4.5 Bicycle infrastructure selection practice

Jurisdictions often develop formal warrants and standards to guide the selection of infrastructure based on various input variables. Few warrants or standards exist for bicycle infrastructure selection as revealed in Figure 4-3 where 15% of large municipalities, no small municipalities, and 18% of provinces indicated that they had them. The survey sought to understand the input variables being used by jurisdictions for these formal warrants/standards, informal policies/practice, or if any other input variables would be beneficial to consider in the future or not at all. This section discusses the use of input variables, which have been categorized as roadways characteristics, safety considerations and bicycling characteristics, based on survey responses.

Figure 4-3: Jurisdictions that have developed bicycle infrastructure selection warrants or standards



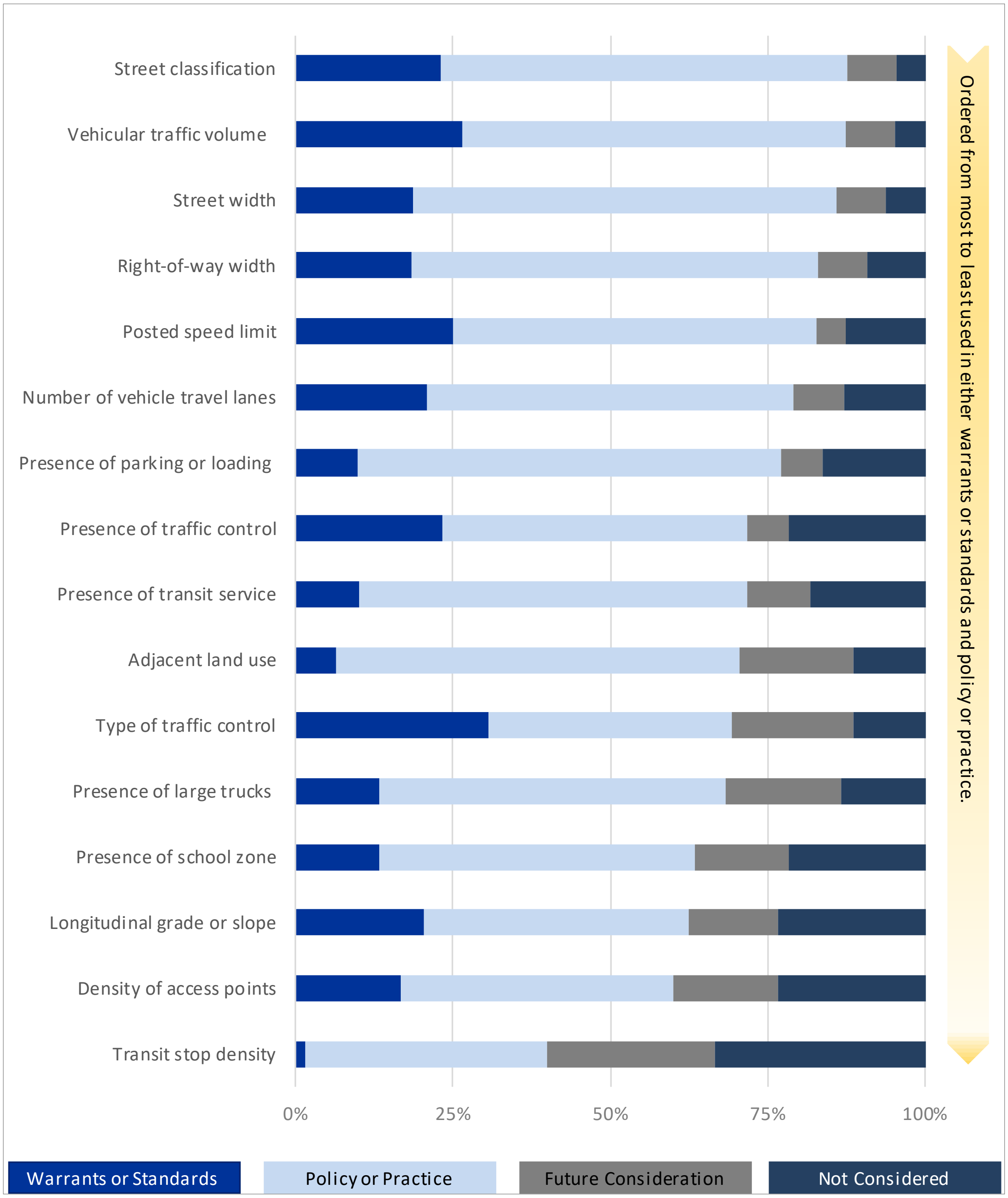
4.5.1 Roadway characteristics

Figure 4-4 shows the roadway input variables considered for the selection of bicycle infrastructure. The following can be observed from the table:

- Street classification is the most commonly used input variable (88%) in formal warrants/standards and informal policies/practice combined. This may be because street classifications are often defined by a range of input variables like vehicular traffic volume, vehicle travel lanes and posted speed limits.
- Street classification, vehicular traffic volume, street width, right-of-way width, posted speed limit, number of vehicle travel lanes, and presence of parking or loading were identified by over 75% of all respondents as currently being used for bicycle infrastructure design.
- Transit stop density was the variable identified by the lowest number of jurisdictions (40%) as being used as input, and 30% indicated they will not consider this input variable.

- Type of traffic control was the most commonly identified input variable (31%) used in formal warrants/standards. However, type of traffic control ranks 11th amongst variables when policy/practice is considered with only 70% of respondents indicating they are used.

Figure 4-4: Bicycle infrastructure selection input variables – roadway characteristics



4.5.2 Safety considerations

Figure 4-5 shows the safety input variables considered when selecting bicycle infrastructure. When compared with roadway characteristics, safety considerations are not as commonly used as input variables for the selection of bicycle infrastructure. Key observations from the figure are:

- Potential conflicts or collisions between bicycles and vehicles are considered in warrants/standards or policies /practices by 56% of respondents.
- Expected motorist compliance is considered in warrants/standards or policies /practices by 52% of respondents.
- Potential bike and pedestrian collisions or conflicts are considered in warrants/standards or policies /practices by 48% of respondents.
- The proportion of respondents that do not consider any of the four safety considerations when selecting bicycle infrastructure is less than 25%.

4.5.3 Bicycling characteristics

Figure 4-6 shows the bicycling input variables considered in the selection of bicycle infrastructure. Key observations from the figure are:

- Route connectivity and closing gaps in bicycle infrastructure are each currently being used by over 75% of all respondents. Both input variables focus on completing a bicycle network.
- Over half of respondents currently use bicycle and pedestrian volume as an input variable to selecting bicycle infrastructure to implement.
- Almost half of respondents do not consider using climate or bicyclist delay as an input variable. However, bicyclist delay is considered as an input that could be used in the future by about 40% of the jurisdictions.

Figure 4-5: Bicycle facility selection input variables – Safety considerations

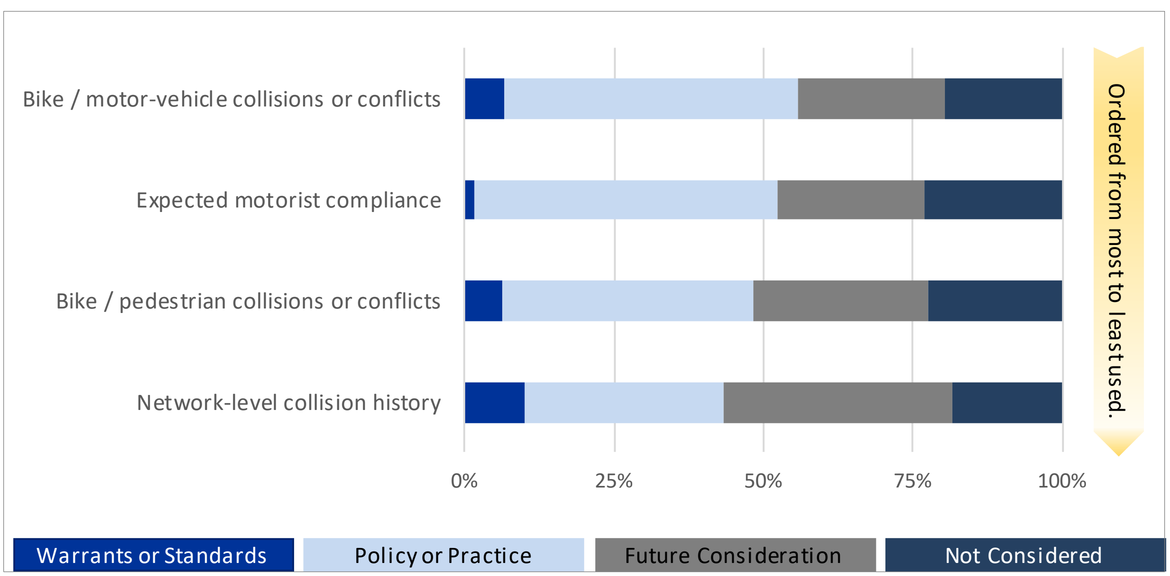
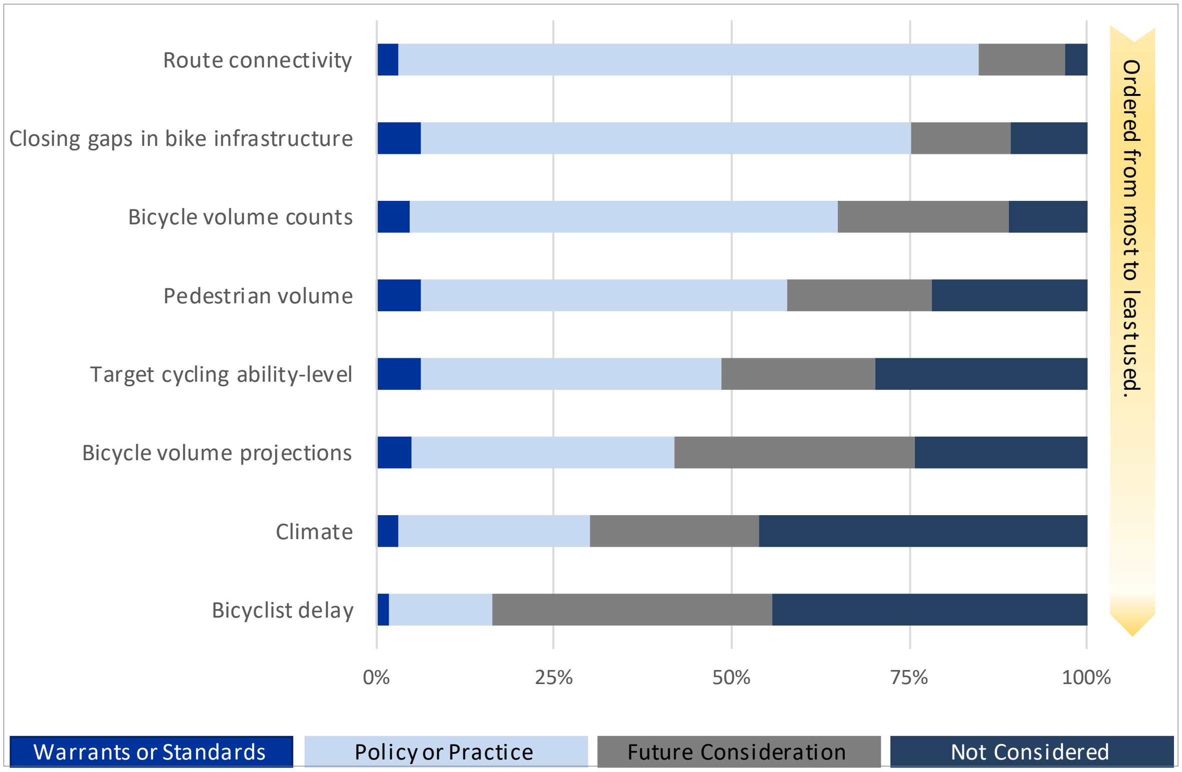


Figure 4-6: Bicycle infrastructure selection input variables – Bicycling characteristics



4.6 Summary of findings

This section provides a summary of the findings from the previous sections.

4.6.1 Application of guidelines

There are three national guidelines that are commonly used by Canadian jurisdictions for bicycle infrastructure selection and design:

- TAC (2017) Geometric Design Guide for Canadian Roads (GDG), 4th edition
- TAC (2012) Bikeway Traffic Control Guidelines for Canada, 2nd edition
- NACTO (2014) Urban Bikeway Design Guide, 2nd edition

4.6.2 Bicycle facilities and intersection treatments

The most commonly implemented bicycle facilities in Canada are off-road multi-use pathway and painted bicycle lanes. These are considered separated bikeways in the TAC GDG and comprise dedicated space for bicyclists and pedestrians on multi-use pathways, separate from motorized traffic. Bike accessible shoulders and major street shared lanes were identified as the third and fourth most commonly-implemented facilities by all responding jurisdictions. These are considered unseparated facilities in the TAC GDG and require bicycles to share roadway space with motorized traffic. Bike accessible shoulders are particularly popular in provincial/territorial jurisdictions. Protected bicycle lanes and buffered bicycle lanes are commonly used by large municipalities but less commonly-used by small municipalities and provinces/territories.

With respect to intersection treatments, gates, fencing and bollards are the most common intersection treatment used by all respondents. Cross-rides are the second most commonly used intersection treatment by responding large municipalities. Other common intersection treatments in large municipalities are bike boxes, intersection crossing markings, and bend-in intersection approaches. Intersection crossing markings and bend-in intersection approaches are the most common intersection treatments used by small municipalities and provinces/territories.

4.6.3 Bicycle infrastructure safety evaluation

The most common bicycle volume data source is the use of counts on an ad-hoc basis as needed or requested. In general, this method of collecting bicycle exposure data is unpredictable and does not provide good temporal variation data that would be produced by a bicycle-specific scheduled monitoring program. Some large municipalities have implemented a scheduled monitoring program that includes bicycles. However, this is not the case for small municipalities or provinces/territories, where scheduled bicycle data collection is rare.

Manual counters were identified as the most common choice for measuring bicycling exposure by all respondents. Manual counters are associated with high accuracy and provide the ability to collect demographic information. However, they only comprise a short-duration and may not provide exposure data that represents average conditions of the required time-period.

The lack of good bicycle safety data was identified as a barrier to evaluating safety performance by all participants. Jurisdictions require good sources of bicycle safety data to safely plan and design for bicyclists in their infrastructure. Bicycle collision data from police records was identified as the most common source of bicycle safety data by all jurisdictions. Other common sources include public feedback and manual observations.

With respect to injury severity, minor injuries (not admitted to hospital) was identified as the least likely level of collision severity to which all respondents would have access. This may be because police records (the most common source of bicycle safety data) are generally submitted if there is significant injury or property damage that results from a collision. An alternative source for minor injury data was identified by three respondents to be bikemaps.org, which collects public accounts of bicycling collisions and near-miss events (crowd sourced).

4.6.4 Bicycle infrastructure selection

In general, provinces and territories seem to focus on developing warrants to decide whether infrastructure is required while large and small municipalities investigate the appropriate application of various bicycle infrastructure.

Street classification is the most commonly used input variable in formal warrants and informal policies. This may be because street classifications are often defined by a range of input variables like vehicular traffic volume, vehicle travel lanes and posted speed limits. Therefore, street classification inherently considers these other input variables.

Safety consideration input variables are not a commonly used input variable by respondents for the selection of bicycle infrastructure when compared with roadway characteristics.

Bicycle characteristics that focus on completing bicycle networks are the most common input variables being used by most respondents. Route connectivity and closing gaps in bicycle infrastructure were identified as the most common variables. Conversely, climate or bicyclist delay are not commonly used as input variables in the selection of bicycle infrastructure.

5. Bicycle infrastructure safety case studies

This chapter presents a summary of findings regarding 13 case studies conducted as part of this project to assess and quantify the safety performance of selected bicycle facilities across Canada and internationally. It also identifies lessons learned for consideration in the development of the facility selection flow chart. In addition, for the purpose of this project, case studies were also used to highlight successes or other experiences resulting from the implementation of different types of bicycle facilities in various settings. A combination of primary and secondary research was used to conduct the case studies. Four of these were based on primary research and the remaining nine were based on secondary research. Details of each case study are included in Appendix D.

Table 5-1 shows the facilities for which case studies were completed, participating jurisdictions, the type of research applied to each case study, and the main sources of information used for each study.

5.1 Canadian facilities

Ten case studies of Canadian bicycle facilities were conducted. These facilities were selected based on information provided through the jurisdictional survey, ensuring the following: geographic representation across the country, and consideration of various bicycle facilities. There was an effort made regarding the consideration of urban vs. rural land uses, however, upon further examination, it was found that there were not existing evaluations or data that could be used to complete a case study.

5.1.1 Off-road bicycle pathway (Waterloo)

Laurel Trail (Central Promenade) is a one-km, two-way, off-road bicycle pathway in Waterloo, which runs through Waterloo Park between Seagram Drive and Erb Street West. The facility, which is designated as part of the Trans Canada Trail, provides a bicycle connection between the University of Waterloo to the north and Waterloo's commercial district to the south. It was upgraded in 2018 from an off-road multi-use path to an off-road bicycle pathway.

The evaluation yielded inconclusive results due to the lack of collision or any other type of information that could be used as a safety surrogate. However, available bicycle volume data showed an increase in bicycles from before to after upgrading the facility, which may suggest that people find the upgraded facility to be more appealing than the previous one, therefore, pointing to increased comfort and/or perceived safety.

Based on the findings from this case study, there is an opportunity for a comprehensive evaluation of the safety performance of off-road bicycle pathways. Important issues that may be worth exploring are:

- The role that these facilities play in the safety of the overall road network.
- Performance during winter conditions, both from the operational and safety perspectives, particularly due to snow accumulation. Do these facilities observe similar bicyclist volumes in winter as in non-winter months?
- How are these facilities being used by bicyclists? Are they for recreational purposes, utilitarian purposes or combinations?

- Safety performance at intersections and perceived safety by various segments of the population.

Table 5-1: Canadian and international case-study participants

Facility type	Jurisdiction	Research type	Main information sources
Off-road bicycle pathway	Waterloo	Secondary	• Report "Upgrades to Central Promenade" • Report "Functional Design of the Central Promenade in Waterloo Park, 2016"
Off-road multi-use pathway	Winnipeg	Primary	• Collision data, bicycle counts, turning movement counts, desktop research
Protected one-way facility	Ottawa	Secondary	• Report "Laurier Avenue Segregated Bicycle Lanes Pilot Project"
Protected two-way facility	Vancouver	Secondary	• Report "Downtown Separated Bicycle Lanes Status Report" (Summer 2011) • Report "Downtown Separated Bicycle Lanes Status Report" (Spring 2012)
Buffered bicycle facility	Toronto	Secondary	• Report "Bloor Street West Bike Lane Pilot Project Evaluation"
Painted bicycle lane	London	Primary	• Collision diagrams • Vehicle and truck turning movement counts • Inductive loop bicycle counts • Results from a network screening of stop-controlled intersections
Major street shared lane	Calgary	Primary	• Turning movement counts before and after. • Bicycle collision data. • Bicycle count data.
Bicycle boulevard	Vancouver	Secondary	• Report "Phase 1 of Point Grey-Cornwall Active Transportation Corridor" (2013) • Report "Phase 2 - Public Realm & Sidewalks Point Grey Road, Alma Street to Tatlow Park" (2016)
Advisory bicycle lane	Ottawa	Secondary	• Journal Paper "Operational Evaluation of Advisory Bike Lane Treatment on Road User Behavior in Ottawa Canada"
Contra-flow bicycle facility	Quebec City	Primary	• Automated bicycle count data • Turning movement counts for before and after facility implementation
Bicycle-accessible shoulder	Florida	Secondary	• Report "An Evaluation of Red Shoulders as a Bicycle and Pedestrian Facility"
Two-way buffered bicycle facility	Chicago	Secondary	• Report "Lessons from the Green Lanes: Evaluating Protected Bike Lanes in the U.S."
Painted bicycle lane	Copenhagen	Secondary	• Journal paper "Bicycle Tracks and Lanes: a Before-After Study" • Report "Effekter af cykelstier og cykelbaner"

5.1.2 Off-road multi-use pathway (Winnipeg)

Northeast Pioneers Greenway in Winnipeg is an off-road multi-use pathway built along a decommissioned railbed between the 4.25-km stretch from Talbot Avenue to Springfield Road in 2009. The Greenway provides a partial north-south connection between northeast Winnipeg and downtown.

Like the previous case, the evaluation yielded inconclusive results due to a variety of issues, including a lack of information about the 'before' situation and some confounding factors in the 'after' situation resulting from the construction of a major connector that may have significantly impacted transportation on this facility.

One of the main challenges associated with this analysis was the fact that there was no clear 'before' situation since limited obvious travel options existed as alternatives to this pathway prior to its implementation. Therefore, the evaluation of this type of facility must follow a careful planning process that specifically addresses the 'before' situation given that off-road pathways may be far removed from the transportation network. This means that one needs to determine what type of data will be collected and where, to establish the benchmark against which the 'after' situation will be compared.

This case study presents a real opportunity for a comprehensive evaluation of the safety performance of off-road multi-use pathways. Important issues that may be worth exploring are:

- The role that these facilities play in the safety of the overall road network
- Performance during winter conditions, both from the operational and safety perspectives, particularly due to snow accumulation. Do these facilities observe similar bicyclist volumes as in non-winter months?
- Safety performance at intersections. In this case bicyclists must dismount and cross at the pedestrian crossing locations
- Perceived safety by various segments of the population
- How to measure the real impact of these facilities on adjacent streets, in terms of collision reduction, comfort, vehicular delay?

5.1.3 Protected bicycle lane, one-way (Ottawa)

The Laurier Avenue West one-way protected bicycle lane in Ottawa was installed along Laurier Avenue West between Bronson Avenue and Elgin Street in 2011. This was done as part of a two-year pilot project to assess the performance of protected bicycle lanes. Laurier Avenue West is a two-way, two-lane arterial roadway in downtown Ottawa, connecting the University of Ottawa and a residential area to the west.

This case study found that one-way protected bicycle lanes can be successfully implemented in a situation where the right of way is available, and intersections allow for the special accommodation of bicyclists. The collision information illustrates a decrease in total collisions as well as a significant decrease in bicycle collision rate. As a result of implementation of one-way protected bicycle lanes, the proportion of bicycle collisions occurring at intersections and those occurring at or near private driveways increased while dooring collisions decreased.

From a safety perception perspective, the introduction of this facility appears to have increased comfort and perceived safety for both bicyclists and pedestrians. However, there is still a challenge regarding how to deal with vehicle parking in the protected bicycle lanes, pedestrians crossing the bicycle lanes without looking, and the requirement for improved clarity and enforcement for both bicyclists and drivers navigating the corridor. Important issues that may be worth exploring are:

- Performance during winter conditions, both from the operational and safety perspectives, particularly due to snow accumulation
- Different treatments to improve pedestrian safety
- Public perception regarding safety and comfort

5.1.4 Protected bicycle lane, two-way (Vancouver)

The Hornby Street two-way protected bicycle lane is a two-way facility extending from Pacific Street to Dunsmuir Street in Vancouver. This bicycle facility, which was built in 2010, provides connection between the Burrard bridge one-way protected bicycle lanes in the south, and the Dunsmuir Street two-way protected bicycle lanes and the waterfront in the north. Hornby Street is a two-lane, one-way minor arterial roadway located in downtown Vancouver.

This case study found that these two-way protected bicycle lanes have led to an increase in bicycle traffic volumes, reduction in bicyclists using the sidewalk, minimal impact to vehicular traffic, safety improvements, and improved public perception regarding these facilities. Important issues that may be worth exploring are:

- Conflict analysis at the various intersection configurations to identify potential safety concerns and to evaluate existing bicycle intersection treatments
- Safety performance over a more significant time period after a facility is implemented
- Any specific issues associated with the interaction of the bicycle facility with trucks and buses
- Accessibility issues for people on wheelchairs (e.g. loading zones and other access points)

5.1.5 Buffered bicycle lane, one-way (Toronto)

The Bloor Street buffered bicycle lane was piloted by the City of Toronto along 2.5 km of Bloor Street between Shaw Street and Avenue Road. The purpose of the pilot was to improve safety and reduce risk for all road users, as well as to reduce impacts to curbside users. Bloor Street is a major arterial roadway, located in downtown Toronto and provides an east-west connection for motorists, bicyclists and pedestrians.

This case study found that a buffered bicycle facility like the one piloted on Bloor Street can have increased demand in terms of cycling volumes as well as potential cycling safety benefits. In addition, the implementation of this facility also resulted in a decrease in vehicular volume and an observed increase in travel time for vehicular traffic. This facility also resulted in decreased conflicts between motor vehicles and bicyclists, motor vehicles and pedestrians, and motor vehicles with motor vehicles. However, there was an observed increase in conflicts between pedestrians and bicyclists, which has been mainly attributed to jaywalking.

From a public perception perspective, the introduction of a buffered bicycle facility has resulted in a significant increased sense of security and comfort for both drivers and bicyclists. Important issues that may be worth exploring in future similar undertakings are:

- The impact on pedestrians in terms of conflicts and/or collisions
- Performance during winter conditions, both from the operational and safety perspectives, particularly due to snow accumulation
- Any specific issues associated with the interaction of the bicycle facility with trucks and buses
- Perceived safety by other segments of the population such as youth
- Accessibility issues for people on wheelchairs (e.g. loading zones and other access points)
- Further exploration regarding the performance of these facilities at intersections

5.1.6 Painted bicycle lane (London)

The Ridout Street painted bicycle lanes were installed by the City of London, Ontario in 2008 along a two-km section of Ridout Street South between Craig Street and Commissioners Road East. Ridout Street South is a north-south primary collector roadway in a residential area.

The evaluation yielded inconclusive results due to a lack of data for the period prior to the installation of the facility. As new painted bicycle lanes are planned, it would be beneficial to collect data prior to implementation and post implementation to enhance the understanding about the safety performance of these facilities. Important issues that may be worth exploring are:

- Safety performance at intersections.
- Safety performance along segments
- Performance during winter conditions, both from the operational and safety perspectives, particularly due to snow accumulation
- Perceived safety by various segments of the population
- Any specific issues associated with the interaction of the bicycle facility with trucks and buses

5.1.7 Contra-flow bicycle lane (Quebec, QC)

The Rue du Pont contra-flow bicycle lane is a 280-m facility installed in Quebec City Rue du Pont from Rue du Prince-Édouard to Rue Saint-Joseph Est in 2016. Rue du Pont is a secondary collector roadway passing through a commercial and residential area.

The evaluation yielded inconclusive results given the limited data available for this facility and the absence of any studies evaluating its performance. Important issues that may be worth exploring in a future evaluation are:

- The impact of a contra-flow lane on pedestrians in terms of conflicts and/or collisions
- Performance during winter conditions, both from the operational and safety perspectives
- Any specific issues associated with the interaction of the bicycle facility with trucks and buses
- Perceived safety by different types of bicyclists

5.1.8 Major street shared lane (Calgary)

The 8th Avenue major street shared lane was installed by the City of Calgary in 2011 along a 900-m segment between 3rd Street SW and 11th Street SW. The facility was replaced in 2015 by a protected bicycle lane in the westbound direction and a buffered bicycle lane in the eastbound direction. 8th Avenue SW is a two-way, two-lane major arterial in downtown Calgary.

This case study yielded inconclusive results but seem to indicate a general increase in safety across the corridor while finding a significant decrease in safety at some intersections. This variable result is common with bicycle safety evaluations due in part to the rare and random nature of bicycle collisions. Important issues that may be explored in the future are:

- The impact of the major street shared lanes on total collisions given that this is a shared facility between bicyclists and vehicles
- The safety performance between major street shared lanes and protected bicycle lanes that were implemented in 2015, three years after the major street shared lanes
- Automated video conflict studies that provide information on collision potential without the need for collisions to occur

5.1.9 Bicycle boulevard (Vancouver)

The Point Grey Road bicycle boulevard between Dunbar Street and MacDonald Street in Vancouver was implemented in 2017, following conversion of Point Grey Road from a collector to a local street in 2014. The Point Grey bicycle boulevard is part of the Seaside Greenway and connects two-way protected bicycle lanes to the east and west in addition to the York Avenue bicycle boulevard in the east.

This case study found that bicycle boulevards can be beneficial to encourage cycling along a facility like that created along Point Grey Road. While the published information used to develop this case study did not provide much insight into the safety performance of the facility, the implementation of this facility has led to a significant increase in bicycle traffic volumes for people of all ages and abilities, and a large decrease in vehicular traffic volume. Anecdotal information presented in the study suggests that the new road feels much safer and there has been a significant increase in women and children cycling. This facility is good candidate for a detailed safety study because of the strong bicycle exposure data from the continuous bicycle count site. Important issues that may be worth exploring are:

- The before-after safety performance of the facility
- Bicyclists perception with respect to comfort and safety when riding on this facility; it would be beneficial to extract these perceptions by gender, age and bicycling ability
- Safety performance at intersections
- Implications regarding connectivity to other elements of the network; this is particularly important for ‘interested but concerned’ commuter bicyclists

5.1.10 Advisory bicycle lane (Ottawa)

The advisory bicycle lanes on Somerset Street East between Chapel Street and Range Road were implemented in 2016 in Ottawa. These lanes are relatively new facilities and the first of their kind in the city and, possibly, in Canada. Somerset Street East is a residential collector with two-way vehicle traffic and time-restricted parking on the north side of the street. The roadway connects the University of Ottawa and Downtown to the Adawe active transportation bridge over the Rideau Canal.

This case study found that advisory bicycle lanes can improve bicyclist safety on roadways with similar characteristics to those of Somerset Street East in Ottawa. Key findings indicate that advisory bicycle lanes encourage bicyclists to travel in the middle of the bicycle lane, increase the distance between passing bicyclists and vehicles regardless of travel direction, and reduce vehicle travel speeds. While this case study presented some positive outcomes resulting from the installation of advisory bicycle lanes, other important issues that may be worth exploring are:

- Safety performance over time (i.e. driver and bicyclist behaviour as the novelty of this new infrastructure subsides)
- Performance during winter conditions, both from the operational and safety perspectives
- Any specific issues associated with the interaction of the bicycle facility with trucks and buses
- Perceived safety by different types of bicyclists
- Safety performance at intersections

5.2 International facilities

5.2.1 Buffered bicycle lane, two-way (Chicago)

The Dearborn two-way buffered bicycle lane was implemented in 2013 in downtown Chicago. Dearborn Street is a northbound one-way, two-lane roadway connecting neighbourhoods north of the Chicago river to downtown Chicago.

This case study found that two-way buffered bicycle facility can significantly increase bicycle volumes and make bicyclists feel safer while cycling. However, area residents perceived the new facility to negatively affect driver and pedestrian safety. The study also indicates that protected bicycle signal phases are an effective way to increase both the actual and perceived safety at signalized intersections on two-way buffered bicycle lanes. Important issues that may be worth exploring in future similar undertakings are:

- Any specific issues associated with the interaction of the bicycle facility with trucks and buses
- The relationship between collisions and conflicts to understand how this method of classifying conflicts relates to actual collisions
- The ability of automated video conflict analysis technologies to collect conflict data that supports this conflict analysis methodology; this type of study could be used to further refine the technology and make conflict analysis more access to jurisdictions

5.2.2 Painted bicycle lane (Copenhagen)

The painted bicycle lanes in Copenhagen are part of an extensive bicycle network of painted lanes installed since the 1980s. A total of 10 bicycle lanes form part of this analysis. Six of the roads where these lanes exist are in central Copenhagen and the other four are just outside of the downtown area. In all cases, these roads are surrounded by mixed land uses (e.g. commercial, residential, institutional functions and recreational).

This case study found that painted bicycle lanes have resulted in negative safety benefits over time from a collision frequency and injury perspective at a network level in Copenhagen. This negative outcome holds true for both segments and intersections. Given the discrepancies between this study and current North American knowledge regarding the safety performance of bicycle lanes, it is important to continue to investigate this issue further, using extensive before and after data for a variety of locations. Copenhagen is one of the leaders in the world when it comes to road safety and the accommodation of bicyclists in urban infrastructure. The findings from this evaluation raise an important issue that warrants further investigation in Canada.

5.2.3 Bicycle-accessible shoulder (Lake County, Florida)

The Lake Country bicycle-accessible shoulder is a two-km facility piloted along a stretch of Lakeshore Drive between Tavares and Mount Dora, Florida. The purpose of the pilot was to determine the impact that a coloured shoulder would have on bicyclist safety. Lakeshore Drive is approximately eight kilometers long and connects Tavares and Mount Dora, a pair of communities located about 60 kilometres northwest of Orlando. The road is under both city and county jurisdiction, but maintenance is performed by the county. This is a rural facility for most of its length, except the portions that traverse each town.

This case study found a positive outcome regarding the performance of this bicycle facility from the safety and perceived safety perspective. However, despite the observed success, the facility has been removed and nothing has been installed in its place.

In researching information for this case study, it became evident that there is a significant knowledge gap regarding the safety performance of bicycle-accessible shoulders. No evaluations exist in Europe since the European Union prohibits the use of shoulders for bicycling. According to the Vienna Convention "[Bicyclists] are required to use bicycle lanes and tracks. They may not, however, use motorways and similar roads." To address this issue, some European countries are implementing 'cycle superhighways,' which are off-road bicycle facilities that connect urban centers.

Because of the importance of evidence-based decision-making, coupled with research identified in this project on the truck-related air turbulence effect on bicyclists riding on highway shoulders, it is essential that research be done on the safety performance of highway shoulders as bicycling facilities in Canada.

5.3 Summary of findings

The purpose of these case studies was to obtain a better understanding regarding the safety performance of different types of bicycle facilities based on experiences from Canadian and international jurisdictions. This understanding is an important part of the information to consider in the flowchart development and gap analysis of this project.

The observed and perceived safety performance of the bicycle facilities covered by the case studies is summarized in Table 5-2. The table also shows the data that was available before and after the facility was implemented. It should be noted that the quality of information available is not shown in the table and is not equal between case studies. For example, the table indicates that many case studies had bicycle volume data for the before and after period, however, very few case studies had strong bicycle volume data comprising more than a short-duration count spanning a few hours.

Table 5-2: Summary of bicycle facility safety performance results from the case studies

Facility type	Previous facility type	Safety performance	Perceived safety/comfort	Data available[1]				
				Reported collisions	Conflicts	Perception survey	Bicycle volumes	Vehicle volumes
Off-road bicycle facility	Off-road multi-use path		●[2]				B/A	
Off-road multi-use path	No bicycle facility, major arterial			B/A			A	B/A
Protected bicycle lane (*one-way*)	No bicycle facility, major arterial	●	●	B/A		A	B/A	B/A
Protected bicycle lane (*two-way*)	Painted bicycle lane (one-way)	●	●	B/A		B/A	B/A	B/A
Buffered bicycle lane (*one-way*)	No bicycle facility, major arterial	●	●	B/A	B/A	B/A	B/A	B/A
Buffered bicycle lane (*two-way*)	No bicycle facility, major arterial (one-way)		●		A	A	B/A	
Buffered bicycle lane *(contra-flow, one-way)*	No bicycle facility, collector roadway		●[2]				B/A	B/A
Painted bicycle lane	No bicycle facility, collector roadway			A			A	A
Bicycle accessible shoulder	No bicycle facility, undivided rural roadway	●	●		A	A	A	B/A
Major street shared lane	No bicycle facility, major arterial	■[3]		B/A			B/A	B/A
Bicycle boulevard	No bicycle facility, collector roadway		●[2]	B			B/A	B
Advisory bicycle lanes	No bicycle facility, local roadway	●			B/A			

● Positive safety outcome
■ Negative safety outcome
1: 'B' indicates data available for the before period and 'A' indicates data available for the after period. This indicates the availability of each data type and does not indicate the data is of good quality.
2: increase of perceived safety and comfort based on increase of bicycle volumes.
3: decrease in safety performance based on safety issues identified at intersections.
Blank cells indicate no data available or insufficient data to measure safety outcomes.

After completing 13 case studies it is evident that knowledge about the safety performance of different bicycle facility types is limited in Canada. Part of the reason is that not many formal evaluations have been conducted by jurisdictions once facilities are installed, which posed a challenge for situations where the case study relied on secondary research.

Part of the safety management process involves evaluating the safety performance of treatments. In many cases bicycle facilities are installed because they are believed to improve bicycle safety. This belief results from available, although limited, literature which has shown that safety or operational benefits can be attained by separating bicyclists from vehicular traffic. However, bicycle infrastructure is not always implemented as part of a systematic approach to improve safety, but rather, as part of an overall approach to expand active transportation networks. Once implemented, the safety performance of these new facilities is seldom evaluated.

One of the challenges associated with many of the case studies was the lack of available data or information to properly assess the safety performance of the facilities. The following challenges were encountered regarding work based on secondary research:

- Not many formal evaluations were publicly or readily available.
- Some of the available evaluations were missing important information such as traffic volumes, public opinion, or even collision data.
- Some of the evaluations were several years old.
- Some of the evaluations were not rigorous enough.
- Unless specifically analyzed as part of a study, no information about the safety performance of facilities on segments versus intersections was available.

In situations where the case study relied on primary research, the following challenges were encountered:

- There is a significant lack of all types of data for post-installation of facilities, including for older facilities.
- In some instances, there is neither before nor after data associated with a facility.
- In some cases, jurisdictions have stopped collecting data post installation and the only available data is limited and old.
- No formal information exists on public opinion regarding bicycle facilities.

6. Facility selection flowchart

This chapter discusses the development and application of a flowchart that can assist practitioners in providing considerations to better inform the selection of a suitable bicycle facility. The development of this flowchart was based on four principal sources of information:

- The comprehensive review of literature
- The end user survey
- The jurisdictional survey
- Lessons learned from the case studies

When using this flowchart, it is important to understand the following: (1) the flowchart is not intended to function as a guideline but rather a probing source in the selection of a facility; and (2) significant knowledge gaps exist with respect to many of the factors considered here and their actual impact on bicyclist safety and comfort. As a result, aside from vehicular speed, for which there is available safety information, all thresholds provided in the flowchart are qualitative in nature (e.g. "low or high") and no quantitative thresholds are identified. It is important that each jurisdiction selecting to apply this flowchart consider developing their own threshold values for the various parameters identified in the flowchart and findings from future research evaluations.

A main assumption for the development of this flowchart is that there is an existing process by which the practitioner has already defined corridors where there are opportunities to install bicycle facilities. In other words, when this chart is consulted, questions regarding right-of-way availability, routing and other infrastructure attributes have already been addressed, and the next step in the process is the actual selection of the most appropriate type of bicycling facility for the given conditions.

The facility selection flowchart is shown in Figure 6-1. Except for off-road pathways, which are feasible on paved or granular road surfaces, bicycle facilities are only feasible where the road surface is paved.

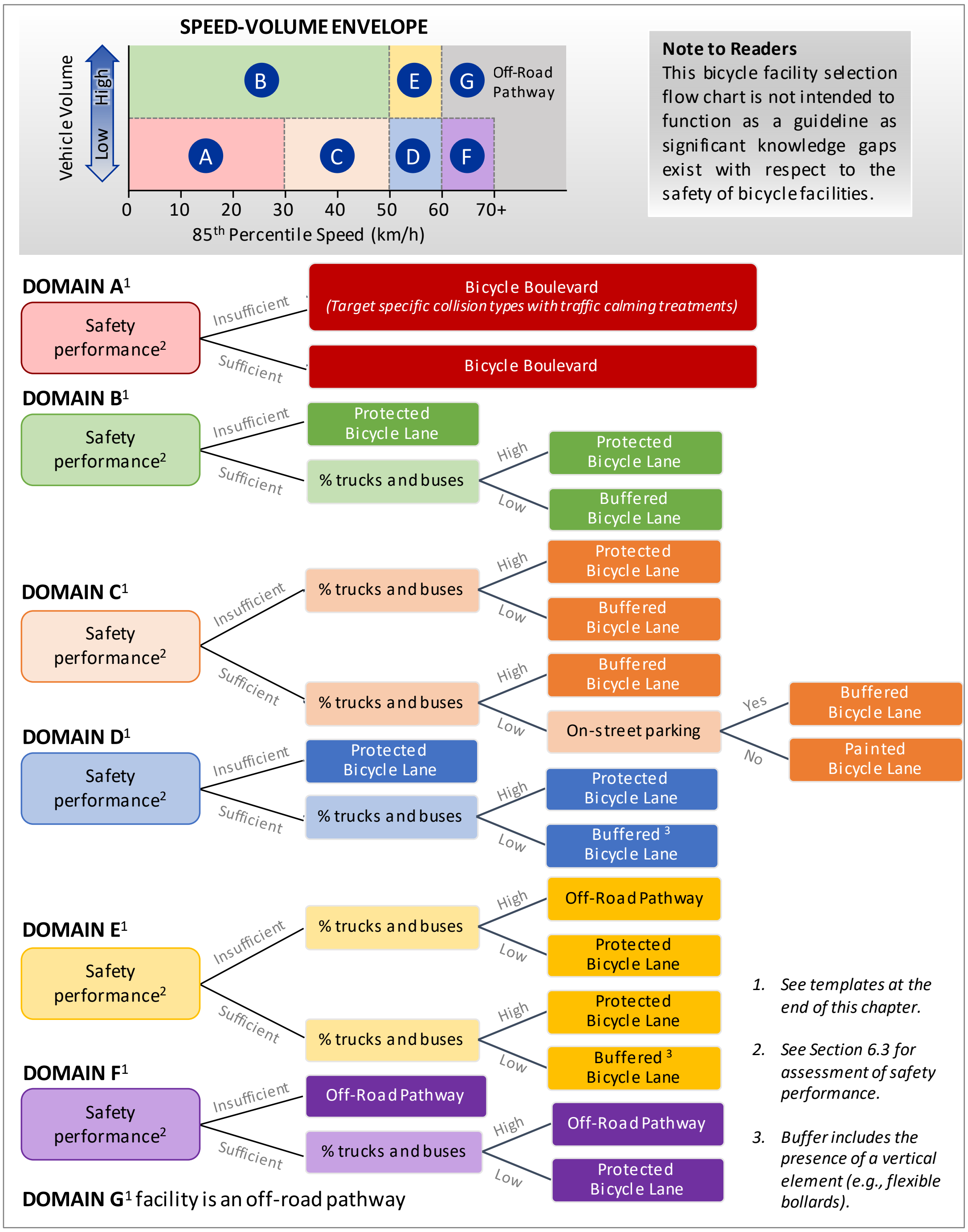
The following discussion addresses each of the components of the chart and explains its application.

6.1 Speed-volume envelope

The first step in the application of this flowchart is to decide what *domain* best describes where the given facility is to be installed based on segment characteristics.

Based on the various information sources used in this study, vehicular volume and operational vehicular speed were deemed to be the two most important factors associated with bicyclist safety and comfort. As shown in Figure 6-1, there is a speed-volume envelope that includes seven distinct combinations (*domains)* of 85th percentile speed and vehicular volume. These *domains* are based on available research that has identified differences regarding bicyclist safety and comfort at the speeds shown for each *domain*. The 85th percentile speed is used because it represents operating speeds, whereas design speed does not. While the horizontal axis clearly marks 85th percentile speed values, the vertical axis is qualitative in nature. This is because no conclusive evidence was found, from the safety perspective, regarding the vehicular volume thresholds that would result in decreased safety and comfort for bicyclists. Therefore, it is important that each jurisdiction determine how these qualitative thresholds would best translate into quantitative guidance, based on their specific characteristics and conditions, and findings from future research evaluations. TAC's *Geometric Design Guide for Canadian Roads*, as well as NACTO provide information regarding various vehicular volume levels associated with different facility types. However, there is no documented evidence that points to safety performance or bicyclist comfort as the determinants for those thresholds.

Figure 6-1: Bicycle facility selection flow chart



6.2 Domain templates

The second step in the application of this flowchart is to consult the *domain template* corresponding to the applicable *domain* and to follow the Bicycle Facility Selection Factors tree to select a bicycle facility. Figure 6-1 cannot be used by itself as there is important information contained in each of the domain templates located at the end of this chapter.

The research found that, in addition to vehicular volume and operational vehicular speed, the following factors also impacted bicyclist safety and comfort: collisions, percent trucks and buses, parking presence, frequency of access points (e.g. driveways), and bicyclist volumes. Collisions as well as percent trucks and buses are explicitly considered in the flowchart for each of the different *domains*, as shown in Figure 6-1. The remaining factors are addressed in a series of templates that have been developed for each of the *domains*, and which are shown at the end of this chapter. Frequency of access points is primarily a design consideration following facility selection, parking presence and bicyclist volume are primarily capacity issues, which are offset by safety performance but should still be considered following the selection of the facility.

Each domain template presents information on bicycle facility selection factors, compatible intersection treatments, and a list of considerations that can assist practitioners improve bicycle safety when implementing a facility.

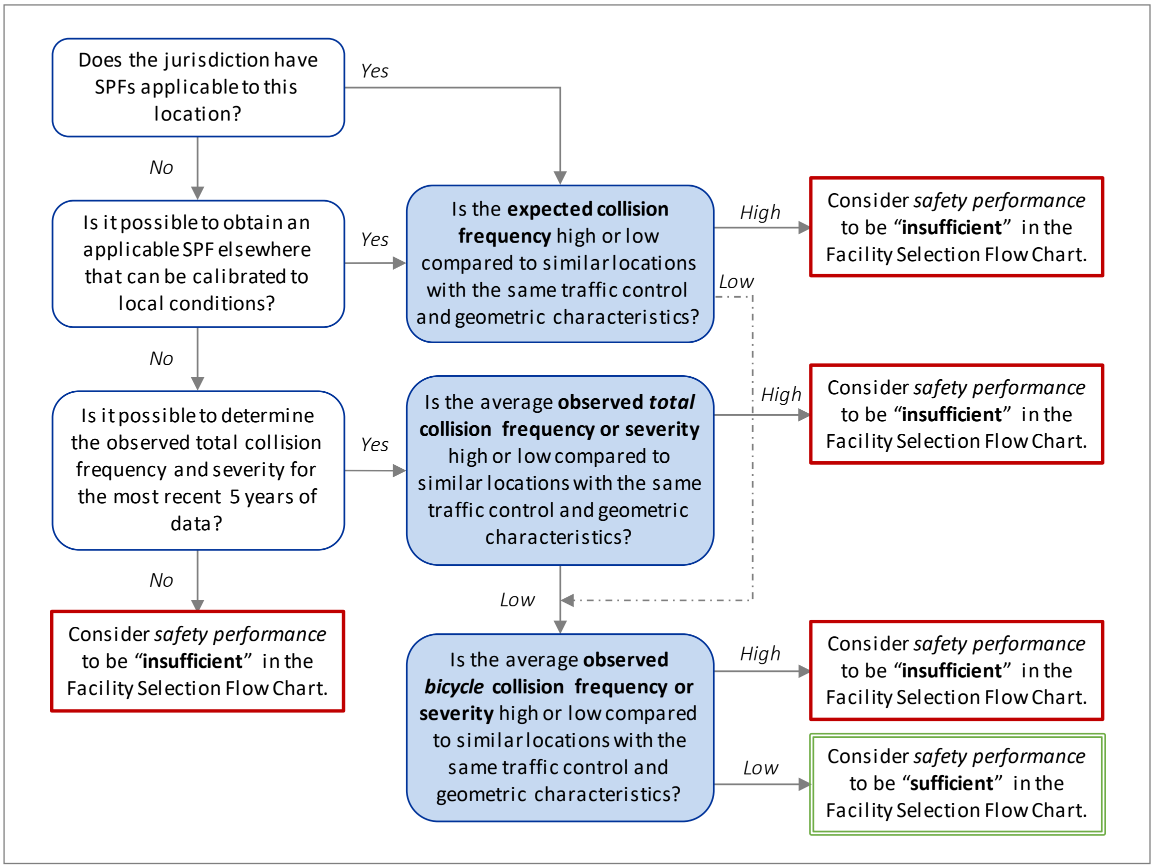
6.3 Safety performance

As shown in Figure 6-1, the first parameter that practitioners need to evaluate in the bicycle facility when applying the flowchart under any *domain* is safety performance, both along segments and intersections. For the purposes of this flow chart, safety performance is defined by expected collision frequency or observed collision frequency and severity:

- *Expected collision frequency* is determined as a function of traffic exposure and roadway characteristics using safety performance functions (SPFs). Some jurisdictions have invested significant resources toward developing SPFs for different locations as a function of exposure and road or intersection characteristics (e.g. number of lanes or type of traffic control). While it is unlikely that there are SPFs available to predict collision frequency involving bicycles only, the SPFs can predict collision frequency for all traffic.
- *Observed collision frequency and severity* is defined as the number of collisions recorded by type and severity per unit of time on a given road segment or intersection. When analyzing total observed collision frequency (vehicular and non-vehicular), it is common practice to use collision data for the most recent three to five years of available information. However, if bicycle collisions are being analyzed in isolation, practitioners should consider using 10 years of data.

This study has found that there are significant limitations regarding the type of data collected and maintained by jurisdictions. Therefore, when addressing the safety performance parameter in the flowchart, practitioners should consider the guidance provided in Figure 6-2. As the figure shows, the preferred type of information to address the safety performance question in the flowchart is the existence of SPFs for the applicable situation. In their absence, practitioners could reference existing SPFs from a similar facility elsewhere and calibrate them to local conditions, as long as the locations being compared have similar design and operational characteristics. The body of knowledge regarding expected safety performance for a given combination of motor vehicle traffic volume and road characteristics has grown extensively in recent years, and it is a great resource for situations where no local information is available. If no SPFs exist elsewhere then practitioners may use observed collision frequency. The two safety performance outcomes identified in Figure 6-2 are “sufficient” or “insufficient” (i.e. average safety performance as for similar locations or safety performance that needs improvement).

Figure 6-2: Safety performance evaluation tool



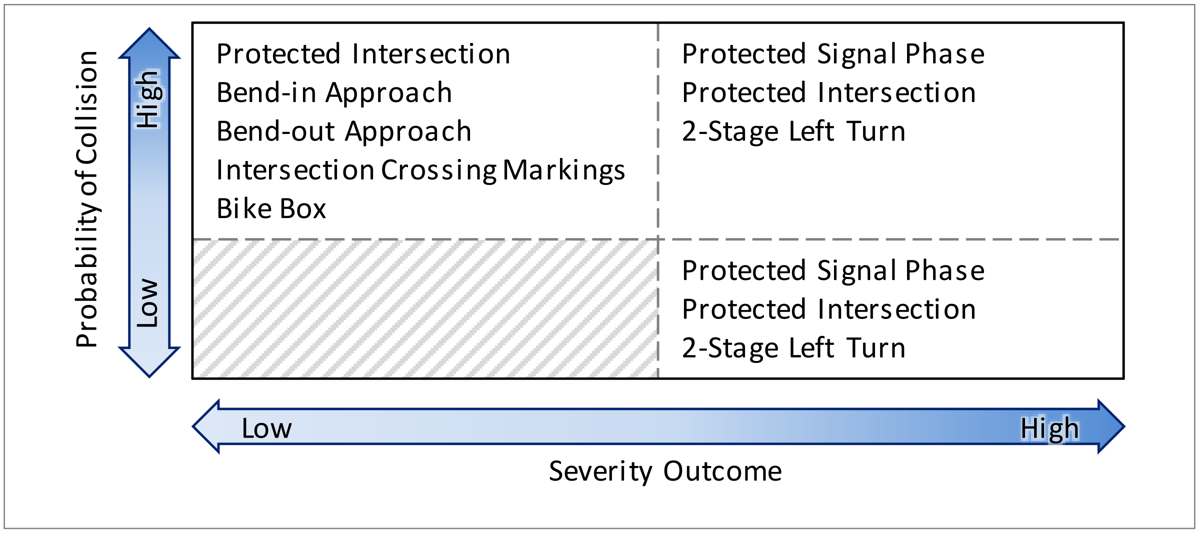
6.4 Intersection treatment selection

The *domain templates* also assist the practitioner with the identification of compatible intersection treatments for the facility that has been selected for the adjacent segments, taking into consideration exposure to risk (i.e. the probability of collision and the injury severity outcome).

The selection of intersection treatments is based on the principle of exposure to risk, where the various intersection treatment types addressed in this report were assessed based on their best fit for a given level of risk at an intersection. For example, an intersection with a high probability of collisions and the likelihood of a high severity outcome, could benefit from any of the following: protected signal phase; protected intersection treatment; or a two-stage left turn.

While this flowchart addresses intersections treatment selection as a function of safety performance, there are operational factors that should be considered when implementing a certain type of treatment, for example, number of left-turning bicyclists, number of left-turning vehicles in the opposing direction, number of lanes, type of bicycle facility along the segment leading to the intersection (to ensure compatibility between the segment treatment and the intersection treatment), pedestrian volumes, and others. Figure 6-3 shows the preferred intersection treatment types for various levels of exposure to risk, based on findings from the literature.

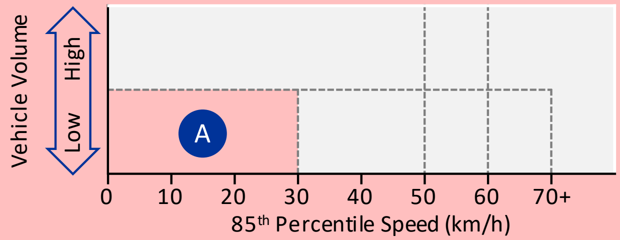
Figure 6-3: Intersection treatment types based on exposure to risk



Note: Gates are an intersection treatment that serves a purpose other than crossing at an intersection. They may be used to reduce bicyclist approach speed on off-road pathways.

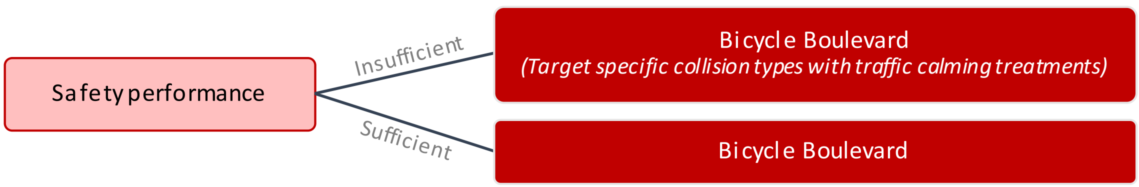
DOMAIN TEMPLATE A

Low vehicular speed and low traffic volume



This domain generally comprises residential or local streets where the 85th percentile speed is 30 km/h or lower and the vehicular volume is low.

BICYCLE FACILITY SELECTION FACTORS



COMPATIBLE INTERSECTION TREATMENTS

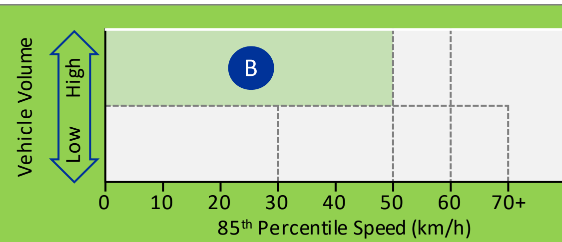
Because this domain has a low exposure to risk, there is not an inherent need for the intersection treatments considered in this report. Practitioners may choose to implement traffic calming treatments, such as those included in TAC's *Canadian Guide to Traffic Calming* (2018), to maintain low-volume and low-speed vehicle operation.

SPECIAL CONSIDERATIONS

1. Assess parking availability relative to access points.
2. Assess access frequency and available sightlines.
3. Assess the need for NO RIGHT TURN ON RED at signalized intersections.
4. Assess street lighting for continuous and uniform illumination supply.

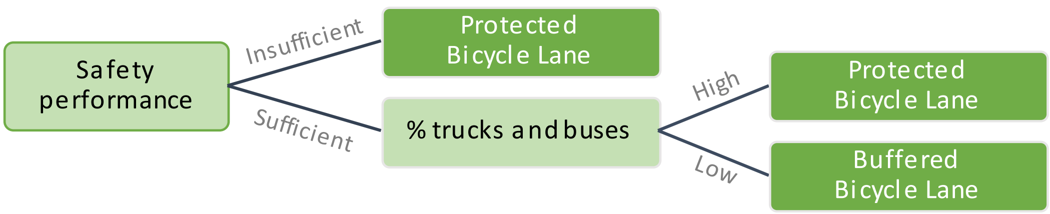
DOMAIN TEMPLATE B

Relatively low vehicular speed and high traffic volume



This domain generally comprises collector, downtown streets, and streets in areas with higher density and mixed land use where the 85th percentile speed is less than or equal to 50 km/h, and the vehicular volume is high.

BICYCLE FACILITY SELECTION FACTORS



COMPATIBLE INTERSECTION TREATMENTS

For locations with *low severity outcome*:

- Protected intersection
- Bend-in and bend-out approaches (only for protected or buffered bicycle lanes)
- Intersection crossing markings
- Bike box

For locations with *high severity outcome*:

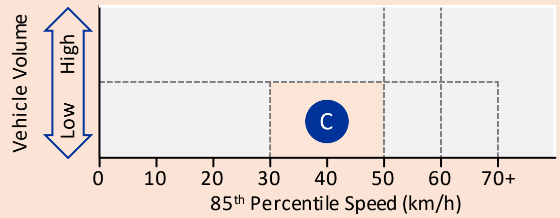
- Protected signal phase
- Protected intersection
- 2-stage left turn

SPECIAL CONSIDERATIONS

1. Assess potential conflicts with on-street parking availability.
2. Assess access frequency and available sightlines. This is particularly important if parking is between the travel lane and the bike facility.
3. Assess truck and bus volume, particularly regarding low speed off-tracking (turning maneuvers).
4. Assess exposure to risk for left turning bicyclists on multi-lane roads.
5. Assess conflicts between pedestrians and bicyclists at intersections.
6. Ensure access for people with disabilities is provided, where needed.
7. Assess the need for NO RIGHT TURN ON RED at signalized intersections.
8. Assess street lighting for continuous and uniform illumination supply.
9. On two-way streets, one-way bicycle facilities on both sides of the street are safer than a single two-way facility on only one side of the street, particularly crossing intersections.

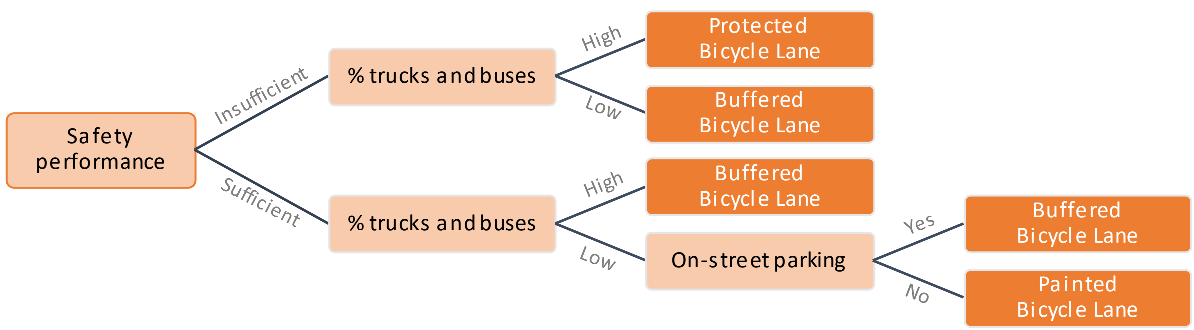
DOMAIN TEMPLATE C

Relatively low vehicular speed and low traffic volume



This domain generally comprises local and collector streets where the 85th percentile speed is above 30 km/h but less than or equal to 50 km/h, and the vehicular volume is low.

BICYCLE FACILITY SELECTION FACTORS



COMPATIBLE INTERSECTION TREATMENTS

For locations with *low severity outcome*:

- No inherent need for the intersection treatments considered in this report

For locations with *high severity outcome*:

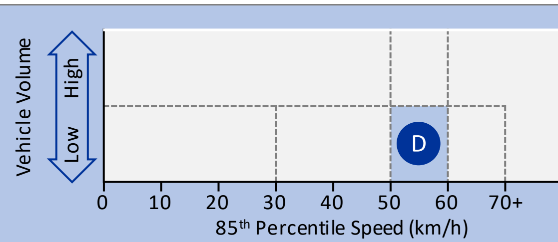
- Protected signal phase
- Protected intersection
- 2-stage left turn

SPECIAL CONSIDERATIONS

1. If cycling volume is high, consider a protected bicycle lane in place of a buffered lane to physically channelize bicyclist s.
2. Assess potential conflicts with on-street parking availability.
3. Assess access frequency and available sightlines. This is particularly important if parking is between the travel lane and the bike facility.
4. Assess truck and bus volume, particularly regarding low speed off-tracking (turning maneuvers).
5. Assess conflicts between pedestrians and bicyclists at intersections.
6. Ensure access for people with disabilities is provided, where needed.
7. Assess the need for NO RIGHT TURN ON RED at signalized intersections.
8. Assess street lighting for continuous and uniform illumination supply.
9. On two-way streets, one-way bicycle facilities on both sides of the street are safer than a single two-way facility on only one side of the street, particularly crossing intersections.

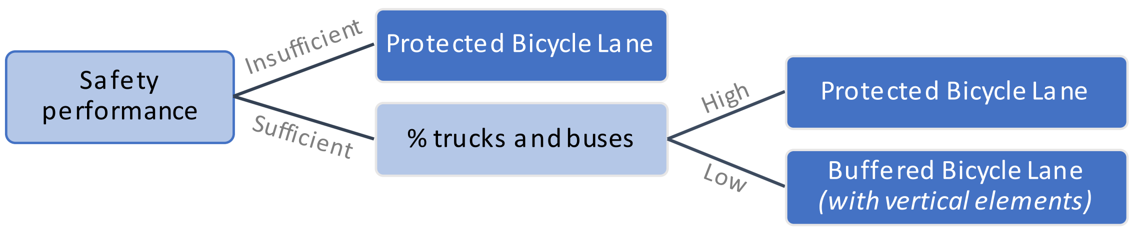
DOMAIN TEMPLATE D

Relatively high vehicular speed and low traffic volume



This domain generally comprises minor arterial streets where the 85th percentile speed is greater than 50 km/h but less than or equal to 60 km/h, and the vehicular volume is low.

BICYCLE FACILITY SELECTION FACTORS



COMPATIBLE INTERSECTION TREATMENTS

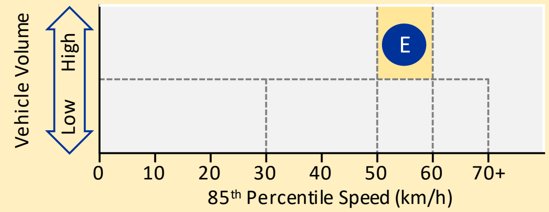
- Protected signal Phase
- Protected intersection
- 2-stage left turn

SPECIAL CONSIDERATIONS

1. Assess potential conflicts with on-street parking availability.
2. Assess access frequency and available sightlines. This is particularly important if parking is between the travel lane and the bike facility.
3. Assess truck and bus volume, particularly regarding low speed off-tracking (turning maneuvers).
4. Assess conflicts between pedestrians and bicyclists at intersections.
5. Ensure access for people with disabilities is provided, where needed.
6. Assess the need for NO RIGHT TURN ON RED at signalized intersections.
7. Assess street lighting for continuous and uniform illumination supply.
8. On two-way streets, one-way bicycle facilities on both sides of the street are safer than a single two-way facility on only one side of the street, particularly crossing intersections.
9. Vertical elements (e.g. flexible bollards) are required to be implemented with buffered bicycle lanes to improve their conspicuity and deter drivers from encroaching into the lane.

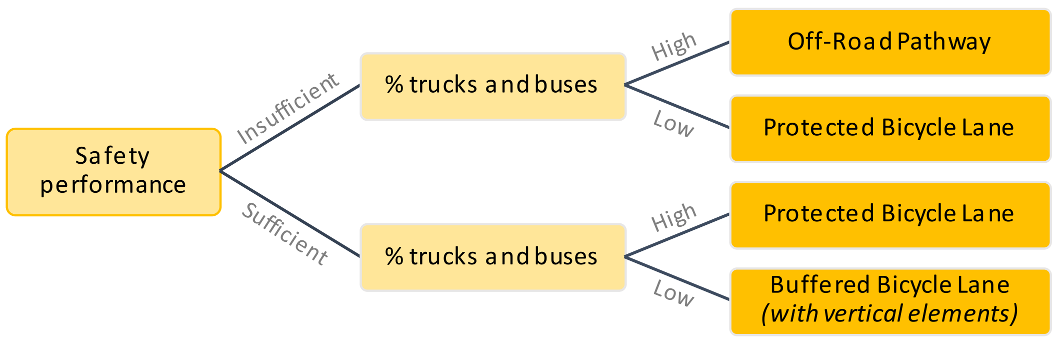
DOMAIN TEMPLATE E

Relatively high vehicular speed and high vehicular volume



This domain generally comprises major arterial streets where the 85th percentile speed is greater than 50 km/h but less than or equal to 60 km/h, and the vehicular volume is high.

BICYCLE FACILITY SELECTION FACTORS



COMPATIBLE INTERSECTION TREATMENTS

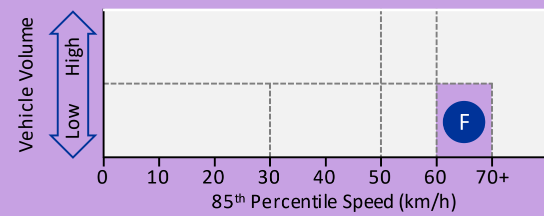
- Protected signal phase
- Protected intersection
- 2-stage left turn

SPECIAL CONSIDERATIONS

1. If cycling volume is very high, consider a protected bicycle lane in place of a buffered lane to physically channelize bicyclist s.
2. Assess potential conflicts with on-street parking availability
3. Assess access frequency and available sightlines. This is particularly important if parking is between the travel lane and the bike facility.
4. Assess truck and bus volume, particularly regarding low speed off-tracking (turning maneuvers).
5. Assess conflicts between pedestrians and bicyclists at intersections.
6. Ensure access for people with disabilities is provided, where needed.
7. Assess the need for NO RIGHT TURN ON RED at signalized intersections.
8. Assess street lighting for continuous and uniform illumination supply.
9. On two-way streets, one-way bicycle facilities on both sides of the street are safer than a single two-way facility on only one side of the street, particularly crossing intersections.
10. Vertical elements (e.g. flexible bollards) are required to be implemented with buffered bicycle lanes to improve their conspicuity and deter drivers from encroaching into the lane.

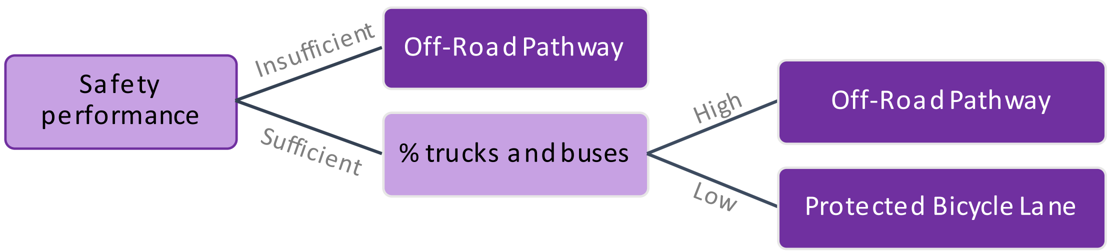
DOMAIN TEMPLATE F

High vehicular speed and low volume



This domain generally comprises major arterials and urban expressways where the 85th percentile speed is greater than 60 km/h but less than or equal to 70 km/h, and the vehicular volume is low.

BICYCLE FACILITY SELECTION FACTORS



COMPATIBLE INTERSECTION TREATMENTS

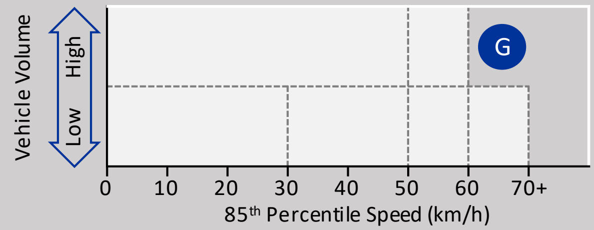
- Protected signal phase
- 2-stage left turn

SPECIAL CONSIDERATIONS

1. Assess potential conflicts with on-street parking availability.
2. Assess access frequency and available sightlines. This is particularly important if parking is between the travel lane and the bike facility.
3. Assess low speed off-tracking (turning maneuvers).
4. Assess conflicts between pedestrians and bicyclists at intersections.
5. Ensure access for people with disabilities is provided, where needed.
6. Assess the need for NO RIGHT TURN ON RED at signalized intersections.
7. Assess street lighting for continuous and uniform illumination supply.
8. On two-way streets, one-way bicycle facilities on both sides of the street are safer than a single two-way facility on only one side of the street, particularly crossing intersections.

DOMAIN TEMPLATE G

High vehicular speed and high traffic volume



This domain generally comprises facilities where the 85th percentile speed is greater than 60 km/h, and the vehicular volume is high.

BICYCLE FACILITY SELECTION FACTORS

The facility type of this Domain should be an off-road pathway. Pedestrian volumes should be explicitly considered to ensure the risk of conflicts between users is minimized or eliminated.

COMPATIBLE INTERSECTION TREATMENTS

- Protected signal phase
- Bend-in and bend-out approaches (if crossing the minor roadway)

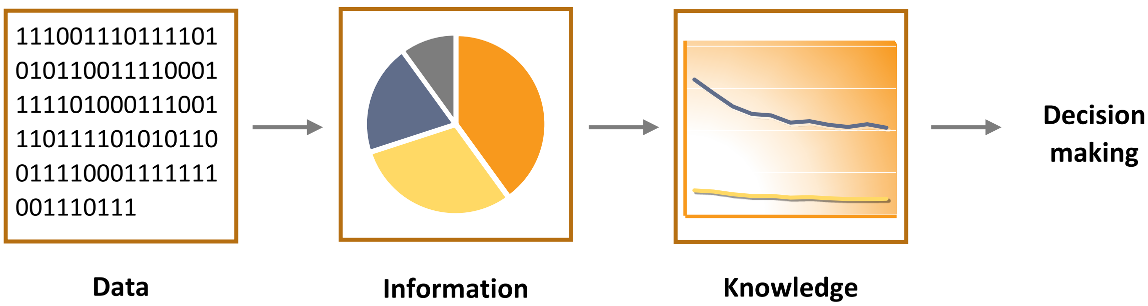
SPECIAL CONSIDERATIONS

1. Assess street lighting for continuous and uniform illumination supply.
2. Ensure pedestrians and bicyclists are properly separated to eliminate conflicts.

7. Gap analysis and discussion

This study revealed a series of data and knowledge gaps associated with the safety performance of bicycle infrastructure in Canada. The distinction between data and knowledge is important given their relative position in the decision-making continuum, where data is important to create information that will generate the knowledge necessary for decision-making. Data alone is of little value without the capability to analyze it and convert it into understanding. Similarly, information can be misused if the correct interpretation is not applied and is of little value if it is not used to produce new knowledge that will lead to understanding of an issue for decision-making. This continuum is illustrated in Figure 7-1.

Figure 7-1: Decision-making continuum from data to understanding



This chapter discusses the findings of this study with respect to data, information, and knowledge gaps about bicycle infrastructure safety. This chapter also provides insight into options that can help close these gaps.

7.1 Data gaps

The study revealed a lack of data across the country to help support evidence-based decisions associated with the provision of safe bicycle infrastructure. An important finding is that currently, bicycle facilities are not well represented in roadway inventory databases, which makes it difficult to study collision causation and bicycle infrastructure safety performance. This has led researchers to collect their own facility roadway data, which varies significantly between studies and are time limited, as there is no ongoing data collection.

In addition, there are significant data gaps with respect to the following: collision and other surrogate safety data, bicycle and pedestrian volume data (exposure data), and vehicular traffic volumes by vehicle type.

7.1.1 Collision and other surrogate safety data

Many jurisdictions have well established collision databases that contain basic collision data such as the date/time, location, collision type and injury classification. The source of the data is typically collision reports from police records. While these collision reports often include collision details about the collision causation, most of the data often focuses on motorized users and excludes non-motorized users. Furthermore, available data suggest that bicyclist-only collisions represent most of the collisions involving bicyclists. Underreporting of bicyclist-only collisions presents a barrier to understanding how the interaction between bicyclists of all abilities and infrastructure impacts safety.

In some instances, researchers have relied on interviews with hospitalized bicyclists to understand the safety performance of bicycle infrastructure to compensate for a lack of police-reported data. In other instances, alternative sources of collision injury severity data have been used such as hospitalization records. Some surrogate measures such as public safety perception or video conflict analysis have also been collected to supplement the evidence-based information obtained from collision data.

The jurisdictional survey revealed that there is a significant lack of reliable bicycle collision data, particularly in small municipalities, which poses a barrier to evaluating safety performance of bicycle facilities or road safety-related infrastructure. Bicycle collision data from police records is the most commonly identified source of bicycle collision data used by Canadian jurisdictions, based on the survey (87% of large municipalities, 47% of small municipalities, 55% of provinces/territories). The survey also revealed that large municipalities seem to have greater access to collision data than small municipalities and provinces across all collision types and injury severity levels.

7.1.2 Bicycle and pedestrian volume data

The lack of bicycle volume data is a crucial limitation of all bicycle infrastructure safety studies. As identified in this study, current bicycle traffic data collection efforts are characterized by short duration counts taken on an ad-hoc basis at locations with high bicycle volumes. As a result, data is insufficient to produce an accurate estimate of annual average daily bicycle traffic (AADB) which is required by the statistical methods to assess the safety performance of any bicycle infrastructure. The jurisdictional survey revealed that most municipalities do not have a regular bicycle counting program in place and only conduct bicycle counts as needed or requested. Most of these counts are done manually and only some large municipalities use video detection, inductive loops and infrared sensors in addition to manual counters for data collection.

Regarding pedestrian volume data, which is important in the evaluation of bicycle infrastructure due to bicyclist/pedestrian interactions, the study found that the most common approach used by jurisdictions across the country is to collect pedestrian data on an as-requested or project-specific basis. Some large municipalities collect pedestrian volume data as part of their vehicle turning movement count programs.

System-wide bicycle and pedestrian traffic monitoring programs are critical to the provision of adequate bicycle and pedestrian volume data needed for high quality safety performance analysis. Yet, guidance for developing these programs and for handling of raw data has only just become available in North America and has not seen widespread implementation in Canadian jurisdictions, as per TAC's *Traffic Monitoring Practices Guide for Canadian Provinces and Municipalities* (TAC, 2017).

7.1.3 Vehicular traffic by vehicle type

Providing an efficient, effective and safe transportation system that moves freight and passengers while accommodating bicyclists can prove to be challenging. This is especially the case in urban environments where trucks and buses are required to maneuver in denser traffic streams, increasing the risk of collisions with other users of the transportation system, including bicyclists.

From a bicycle infrastructure safety perspective, the key issue about vehicular traffic by type is the size of vehicles sharing the road with bicyclists (i.e. the proportion of trucks and buses travelling on the road where bicycle facilities are to be installed or need to be retrofitted). This is important because the end user survey found that the presence of trucks on the road was one of the most important issues impacting safety perception. Further, the literature also found that the presence of bus stops increases bicyclist collision frequency and decreases bicyclist safety perception.

This study found that while there is enough data regarding transit operations (number of buses and bus stop locations) in urban areas, there is limited data regarding the proportion of trucks operating on urban roads. This data is sporadically collected, mainly for special applications.

7.1.4 Facility selection flow chart

Table 7-1 shows the data elements that would be required for the application of the facility selection flowchart (Chapter 6) and their current categorization in terms of whether the data element is routinely collected by transportation agencies or not. As the table shows, there are data gaps that currently exist regarding the following: vehicular traffic operational speed, truck volumes as a proportion of total traffic, collision data (for small municipalities), turning movement counts, bicyclist volumes, pedestrian volumes and frequency of access points. Most of these data elements are sporadically collected.

Table 7-1: Data elements required for the use of the facility selection flow chart

Data elements	Categorization
Operational speeds (for 85th percentile speed)	• Sporadically collected (for special requests)
Traffic counts (for vehicular volume)	• Routinely collected in some urban areas but only for average daily traffic (ADT) estimates • Routinely collected by provincial/territorial governments • Sporadically collected in small municipalities
Collision records by injury severity (for safety performance determination)	• Routinely collected by large municipalities and provincial/territorial governments • Not readily available to some small municipalities
Bicycle collision records by injury severity (for safety performance determination)	• Bicycle/vehicle collision records routinely collected by large municipalities and provincial/territorial government as part of the general collision statistics • Not readily available to some small municipalities
Truck counts (for % trucks)	• Sporadically collected
Bus counts (for % buses)	• Routinely collected in most large municipalities
On-street parking presence	• Not collected but available to most urban areas
Turning movement counts (for turning volumes by direction)	• Sporadically collected in urban areas
Pedestrian counts (for activity at intersections or along segments)	• Routinely collected at signalized intersections in large urban areas • Sporadically collected at non-signalized intersections and along segment in rural and urban areas

Data elements	Categorization
Bicycle counts (for bicycle volumes)	• Sporadically collected by major municipalities (special requests). • Not collected in other jurisdictions
Frequency of access points (driveways)	• Not collected

Jurisdictions that wish to improve their capability to develop safer bicycle infrastructure would greatly advance in this direction by identifying data sources and collection tools. Furthermore, the development of a prioritized list of data elements for collection that can form part of a multi-year action plan can guide the jurisdiction through the data collection process. This is discussed in Section 7.3.

7.2 Knowledge gaps

Road authorities are frequently faced with the need to plan, design and implement bicycle infrastructure based on limited or no safety evidence-based information and knowledge. This study found that existing information and knowledge about the safety performance of bicycle facilities along roadways and bicycle treatments at intersections is very limited. In many cases, bicycle infrastructure has been implemented in response to the increasing demand to accommodate bicyclists throughout the existing road network. However, there has not been a subsequent evaluation of the safety performance of the provided infrastructure to learn for future implementations. As a result, little is known regarding the following in Canada:

- The safety performance of different bicycle facility types and intersection treatment types, including before-after safety evaluations of bicycle infrastructure
- Performance during winter conditions, both from the operational and safety perspectives, particularly due to snow accumulation and icy conditions
- The extent and characteristics of use of different types of bicycle infrastructure – are they for recreational purposes, utilitarian purposes, or combinations?
- The impact of bicycle infrastructure on adjacent streets, in terms of collision reduction, comfort, vehicular delay, redistribution of vehicular traffic, and others
- The issues of importance regarding the implementation of bicycle infrastructure and its interaction with trucks and buses
- Accessibility issues for people on wheelchairs (e.g. loading zones and other access points) in the presence of different types of bicycle infrastructure
- The impact of different bicycle infrastructure types on pedestrians in terms of conflicts and/or collisions
- Bicyclists' perception with respect to comfort and safety when riding on various facility types – are there any differences by gender, age and bicycling ability?
- The safety performance of different types of physical and temporal separation between bicyclists and pedestrians, and bicycles and vehicles
- Thresholds associated with better safety performance for different factors that impact bicycle infrastructure safety (e.g. vehicular volume, bicycle volume, bicycle travel speed, percent of trucks and buses, frequency of access points)

These information and knowledge gaps are discussed more extensively in the following sections.

7.2.1 Safety evaluations

Many agencies still use the naïve before-after study method to evaluate the safety performance of a treatment. As indicated in this report, this method is not considered as a rigorous method in estimating a treatment effect and often produces an inflated treatment effect. Thus, the naïve method is no longer recommended for estimating the safety performance of facilities and treatments. The preferred method for evaluating the safety performance of a facility or treatment is the Empirical Bayes (EB) and full Bayes (FB) methods, which lead to the most accurate and reliable results. The EB and FB methods require annual traffic volume and road inventory data complementing the annual collision data.

Because collisions are random events that naturally fluctuate over time, short-term collision frequencies are not a reliable representation of long-term collision trends at a location. In addition to natural fluctuations, it is statistically probable that a period of high collision frequency will be followed by a period of low collision frequency and vice versa. This tendency is called regression-to-the-mean and can bias research that relies on short-term collision frequencies. Because of this, methods other than EB and FB methods typically used in the past for before-after evaluations are not recommended because they do not account for regression-to-the-mean bias and traffic volume changes that occurred during the study period. However, in the absence of quality data from a sufficient time period before treatment implementation, cross-sectional studies may be used as an alternative, interim source of knowledge. Cross-section regression and case-control methods are two possible cross-sectional study methods. These are discussed in Chapter 2.

7.2.2 Safety impact of different parameters

This study found that there are several factors that specifically affect observed and perceived safety performance of bicycle facilities, for example, vehicle speed, vehicular volume, percent trucks and buses, the presence of parking, frequency of access points (e.g. driveways) and bicyclist volumes. This study also found that significant knowledge gaps exist with respect to all these factors, except for vehicle speed, on how they affect the safety performance of bicycle facilities. Regarding vehicle speeds, there is available research that has correlated observed and perceived safety for bicyclists under different posted or operational speed conditions for vehicular traffic. Beyond this knowledge, there is no documentation regarding the observed or perceived bicyclist safety for different thresholds associated with the other factors, which results in significant information and knowledge gaps for bicycle safety analysis in Canada.

In the case of vehicular traffic volume, while several guides provide daily traffic volume estimates under which certain types of bicycle facilities are feasible, these recommendations are not supported by any type of safety-related research. In addition, there is no consistency in the guidance provided as some guides recommend certain bicycle facilities for vehicular traffic volumes associated with other types of facilities in other guides.

Regarding the other factors, no research was found that conclusively addresses the thresholds at which the safety performance of a bicycle facility change. For example, while the percentage of trucks and/or buses on a street or road is a factor that impacts bicycle safety, it is not known what the percent threshold is between a safer and a less safe situation for bicyclists. The same is true for the frequency of access points, where it is not known what number of access points per kilometer will deem a bicycle facility or situation more, or less safe, for bicyclists.

In the case of bicyclist volumes, research shows that bicyclist safety risk decreases with higher bicyclist traffic volumes. However, there is no documentation regarding the bicycle volume thresholds at which a situation becomes more, or less safe, for bicyclists.

Because of these significant information and knowledge gaps, it is important to collect the data and develop the information for a better understanding about the safety impact of at least each of the following factors on bicyclist safety (observed and perceived) and their associations with different bicycle facility types:

- Vehicular traffic volume
- Percent of trucks or buses
- Frequency of access points

This new information and knowledge will strengthen the usability of the facility selection flowchart and will better assist practitioners in the selection of a suitable bicycle facility for a given set of road conditions.

7.2.3 Safety performance of bicycle facilities

This study found that there are significant information and knowledge gaps regarding the expected safety performance of different types of bicycle infrastructure (both along segments and at intersections). The preferred approach to address the safety performance question is through the use of safety performance functions (SPFs). However, while the body of knowledge regarding expected safety performance for a given combination of vehicular traffic volume and road characteristics has grown extensively in recent years in North America, and it is a great resource for situations where no local information is available, no similar information exists for bicycle traffic volumes. In fact, not many Canadian agencies have yet developed SPFs for their unique transportation conditions, much less, SPFs that are bicycle-specific ones. Some jurisdictions have developed CMFs that have assisted them in the evaluation of the safety performance of new bicycle facilities. Many of these CMFs have become part of the catalogue of CMFs housed by the FHWA CMF Clearinghouse. Practitioners may consult the CMF Clearinghouse for information on the safety performance of specific treatments associated with bicycle infrastructure.

To address this knowledge gap, practitioners may use, in interim, observed collision frequency while enough data is collected to develop jurisdiction-specific SPFs for bicycle infrastructure. Table 7-2 shows different methods used for estimating collisions, their advantages and disadvantages.

7.3 Bicycle infrastructure safety action plan

As previously stated, there are opportunities that can help transportation agencies to close the existing data, information, and knowledge gaps associated with the provision of safer bicycling infrastructure. By developing a multi-year data action plan that identifies data sources and collection tools, and prioritizes data elements for collection, agencies can begin to successfully close existing data gaps. This new data would be used to develop the information and the necessary knowledge that supports decision-making.

A safety action plan is an effective tool to address the findings of this study in terms of evidence-based knowledge needs and data elements required for the selection of bicycle infrastructure. This type of plan can help improve the safety of all road users by providing the jurisdiction's decision-makers with a more reliable, evidence-base source of knowledge.

A safety action plan describes each action, identifies the human and financial resources, defines the timelines for when each action needs to take place, and the party responsible for the action. The priorities given to close the data and knowledge gaps guide the order of the actions, identifying the cycle for update of its actions (e.g. annually or every 2-3 years).

Table 7-2: Methods for estimating collisions

Methods for estimating collisions	Advantages	Limitations
Observed collision frequency and collision rate, are historical collision data and information respectively; they are used for estimating annual average collision frequency and evaluating the effectiveness of a treatment, and to assess the risk for each road user respectively.	• Well understood by practitioners and most of the public. • It is assumed that historical trends will continue to occur in the future. • Most jurisdictions maintain a database of historical collisions.	• Does not account for regression-to-the-mean bias. • Does not account for the non-linear relationship between collision frequency and traffic volume. • Bicycle collisions are infrequent and may require a long time period of homogenous conditions which may not be available or easy to achieve given the infancy of implementation for many bicycle facilities in Canada.
Surrogate safety measures can be used as an indirect measure of observed collisions. They may be based on events that precede a collision (e.g. conflict studies that quantify near-misses) or on a possible causal link to collisions (e.g. age and ability of cycling population).	• Data can be collected as there is no need to wait for collisions to occur. Consequently, this method is more proactive. • May not require a long time-period of data collection and thus can be used on relatively new facilities.	• The relationship between collisions and surrogate safety measures are often unproven and may introduce another source of inaccuracy.

Methods for estimating collisions	Advantages	Limitations
EB and FB statistical methods have been developed using regression analysis to address regression-to-mean bias and reliably estimate expected average collision frequency for existing roadways, future changes to existing roadways, or new roadway designs. The AASHTO Highway Safety Manual (HSM) uses the predictive model which relies on SPFs to estimate the average collision frequency of the base facility type and the Empirical Bayes Method to adjust model if observed collision data is available.	• Can be used to estimate expected average collision frequency for past conditions, future changes to existing roadways, and new roadway designs. • Accounts for regression-to-mean bias. • Does not rely on availability of limited collision data from one specific site. • Accounts for non-linear relationship between collision frequency and traffic volume.	• Statistically more complex to develop than other methods but tools to assist in the development and calibration of SPFs have been developed and are available for all jurisdictions.

7.3.1 Data collection priorities

The identification of data collection priorities is a key step in the development of a safety action plan, and practitioners need to consider available resources in the identification of these priorities. One way in which data collection priorities may be determined involves the following four steps:

Step 1 – Future bicycle infrastructure developments. Identify the roadways and intersections for which bicycle infrastructure is planned in the upcoming years. This is typically related to the jurisdiction's active transportation plan, cycling network, cycling strategies, or vision zero road safety plan. Each location should be identified as current, short-term, medium-term, or long-term project, as per the agency's timelines.

Step 2 – Categorize available data elements. For each of the data elements listed below, identify the quality of each data element at a network level, and consistency of collection. For example, does the agency have a program to regularly collect 85th percentile speeds network-wide? If so, how accurate is the data? The same approach would apply to the other data elements.

- Operational speeds (for 85th percentile speed)
- Traffic counts (for vehicular volume)
- Collision records by injury severity (for safety performance determination)
- Bicycle collision records by injury severity (for safety performance determination)
- Truck counts (for % trucks)
- Bus counts (for % buses)
- On-street parking presence
- Turning movement counts (for turning volumes by direction)
- Pedestrian counts (for activity at intersections or along segments)
- Bicycle counts (for bicycle volumes)

- Frequency of access points (driveways)

Step 3 – Prioritize data elements. Determine the data collection priority based on the data requirements for evaluating the performance of existing facilities first. Then do the same for short-term, medium-term and long-term projects, as per the agency's timelines.

Step 4 – Include data gaps into the Safety Action Plan. Those data elements from Step 2, which are found to be sub-optimal, should be included as part of the action plan for the expansion of the data collection programs in the jurisdiction, prioritized as per Step 3. The new databases will also be valuable when evaluating the safety performance of existing bicycle infrastructure.

7.3.2 Development of new knowledge

In addition to actions that explicitly address data issues, the safety action plan should also include actions that help close knowledge gaps in the jurisdiction, for example, those identified in Section 7.2. While practitioners can be well equipped to conduct the necessary analyses that will convert available data into information that will deliver new knowledge, there are opportunities that will reduce the strain on available agency resources while promoting professional growth. For example, many of these opportunities lie in the development of partnerships with educational institutions to address each of the identified knowledge gaps. The knowledge gaps that have been identified are a good fit for research at the graduate level, particularly given the challenges associated with each question in terms of risk and uncertainty. While the agency is the right candidate to ensure a strong data collection program is implemented and maintained, it is possible to engage educational institutions to develop the new information and disseminate the knowledge that is necessary for future investment in bicycle infrastructure.

The development of new knowledge without dissemination is not desirable, particularly considering the extensive lack of knowledge that currently exists in Canada regarding this subject. It is essential that public agencies not only help create but also disseminate information and knowledge to the community of practitioners for enhanced planning, design, operations and maintenance of bicycle infrastructure. This can be done through the development of guidelines, manuals, research or conference papers, webinars and educational initiatives.

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List of appendices (under separate cover)

A document containing the following appendices can be downloaded from TAC's online publication catalogue at www.tac-atc.ca.

Appendix A – Literature Review

Appendix B – End User Surveys

Appendix C – Jurisdiction Survey

Appendix D – Canadian and International Case Studies

Appendix E – Canadian Academic Survey

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