Lessons Learned from Adopting the Highway Safety Manual to Assess the Safety Performance of Alternative Urban Complete Streets Designs

Sudip Barua
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-399-8073
Email: barua1@ualberta.ca

Karim El-Basyouny, PhD
City of Edmonton Assistant Professor of Urban Traffic Safety
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-492-9564
Email: basyouny@ualberta.ca

Md. Tazul Islam, MSc
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-492-0658
Email: mdtazul@ualberta.ca

Suliman Gargoum
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-200-0161
Email: gargoum@ualberta.ca

Paper prepared for presentation at the Technical Session of the
2014 Conference of the Transportation Association of Canada
Montreal, Quebec

ABSTRACT

A safety assessment of street designs is an essential stage in the planning process of future transportation systems. Such an assessment guides decision-makers in selecting the safest and most sustainable design options. In this study, the Highway Safety Manual (HSM) predictive methods were used to assess the associated safety risks of alternative Complete Streets designs drafted by the City of Edmonton. The City proposed a total of 63 (42 collector, 12 local, and nine arterial road) design drafts. For each of the design proposals, the safety indices were computed and alternative options were compared. The objective of this paper is twofold: i) assess the safety performance of those alternative design drafts; and ii) highlight the lessons learned as well as the issues and challenges faced while using the HSM predictive methods to conduct the assessment. The results obtained from the safety assessment reveal that road cross sections with a large lane width, a large offset of a roadside fixed object, the presence of a median, no on-street parking, and no on-street bike lane have less safety risks compared to road cross sections that do not possess these features. As for the second objective, several issues and challenges were faced: i) unavailability of baseline models for certain site types (e.g., six-lane divided arterial) and roadway categories; ii) difficulties in finding appropriate crash modification factors (CMFs) for some geometric road features; iii) debatable credibility of some of the CMFs as a result of regional factors (e.g., weather, terrain, etc.); iv) the fact that some CMFs were only developed for certain roadway categories or collision severities, while others do not specify the roadway category; thus, using these CMFs is based on assumption; and v) the number of CMFs used to adjust each base model exceeded three, which affects the accuracy of the predicted number of collisions. These issues and challenges may provide a future research direction to enhance the scope of the HSM. Furthermore, the assessment process illustrated herein can be proactively used during roadway planning and design to compute the associated safety risk of different Complete Streets cross sections.

KEYWORDS: Complete Streets Policy, Highway Safety Manual, Crash Modification Factors, HSM Predictive Approach, Calibration Factor.

1. INTRODUCTION

"Complete Streets" is a relatively new transportation policy and design philosophy under which streets are planned and constructed to ensure safe access for all road users (e.g., pedestrians, motorists, bicyclists, etc.) [1]. This policy promotes an effective, equitable, safe, and balanced multimodal transportation system integrated with sustainable land use developments. Conversely, incomplete streets are designed in consideration of vehicles only, which limits the road users' mode choices and makes walking, bicycling, and public transportation seem inconvenient, unattractive, and even unsafe. There are key reasons that more communities are focusing on implementing a Complete Streets policy: i) it creates a comprehensive, integrated, and connected transportation system that supports sustainable development and provides livable communities; ii) it develops a multimodal transportation system that ensures safe and efficient mobility for all types of road users; iii) it provides a flexible transportation network for different types of streets, areas, and users, which is more appealing to residents and good for economic activities and developments; and iv) it reduces traffic congestion and reliance on carbon fuels, thereby, reducing greenhouse gas emission [1, 2, 3].

Complete Streets encourage non-motorized travel and increase the number of people bicycling and walking, thereby, indirectly improving safety. According to Jacobsen [4], as the number and portion of people bicycling and walking increases, roadway fatalities and injuries will decrease. Considering these facts and benefits of a Complete Streets policy, approximately 488 jurisdictions have adopted the policy in the USA and even more jurisdictions are in the process of developing transportation plans that incorporate Complete Streets principles [5]. Similarly, in Canada, six cities and counties (Thunder Bay, Waterloo, Calgary, Mississauga, the Niagara region, Grey County, and Bruce County) have successfully implemented a Complete Streets policy [6]. The City of Edmonton's (COE) Transportation Master Plan, *The Way We Move*, identified Edmonton's need for a Complete Streets strategy to balance and support seven goals: i) transportation and land use integration; ii) access and mobility; iii) transportation mode shift; iv) sustainability; v) health and safety; vi) well-maintained infrastructure; and vii) economic vitality [7, 8]. Therefore, the COE designed different preliminary Complete Streets cross sections for local, collector, and arterial roads in new communities. These cross sections include different geometric and non-geometric road features: sidewalks, bike lanes, medians, lighting, parking, etc.

It is of paramount importance to assess the safety performance of alternative Complete Streets cross sections before constructing roadways. While performing the safety assessment through the Highway Safety Manual (HSM) [9] predictive methodology, several issues and challenges were faced: i) for urban roadways, the HSM focuses only on arterial roadways; no guideline is provided for either urban collector or local roadways; ii) there is a lack of HSM base models for certain roadway types; iii) base conditions were difficult to transfer and calibration factors lacked the strength to replicate actual local roadway conditions; and iv) appropriate and (or) exact crash modification factors (CMFs) for specific road design features were difficult to find in the literature; most of the established CMFs were developed for highways, rural roadways, or urban arterials and focused on certain collision types or severities. Because the available CMFs from other jurisdictions may not be applicable to replicate actual local roadway conditions, various assumptions were made in the analysis to determine the CMFs for specific road design features.

To this end, there are two objectives of this study: (i) illustrate a framework to assess the safety performance of alternative Complete Streets cross sections on urban roadways based on the HSM predictive method [9]; and ii) discuss the main limitations, issues, and challenges experienced throughout the process. The framework proposed herein can be proactively used during roadway planning and design to assess the associated safety risks of different Complete Streets cross sections. Furthermore, the issues and challenges faced while adopting the HSM predictive method may provide a future research direction to enhance the scope of the HSM.

2. CROSS SECTIONS DESCRIPTION

The COE proposed 63 different cross sectional design alternatives; 12 of which were for local roads, 42 for collector roads, and nine for arterial roads. Due to the large number of design alternatives, it was impractical to show all designs in this paper; however, a statistical summary of the geometric and non-geometric road attributes of those cross sections is presented in Table 1. One or more of these attributes varied from one design alternative to another.

Table 1: Statistical Summary of the Cross Sections

Road Class	Attributes	Mean	Std.	Max	Min
Local	Number of Lane	2	0	2	2
	Lane Width (Left) (m)	2.42	0.69	4	1.6
	Lane Width (Right) (m)	2.42	0.69	4	1.6
	Road Width (m)	8.89	1.23	12.50	8.00
	Right of Way (m)	17.13	1.76	21.50	14.40
	Presence of Median	0	0	0	0
	Fixed Object Offset (Left) (m)	1.25	0.26	1.50	1.00
	Fixed Object Offset (Right) (m)	1.90	1.05	4.15	1.00
	Presence of Parking	1	0	1	1
	One Sided Parking	0.42	0.51	1.00	0.00
	Both Side Parking	0.67	0.49	1.00	0.00
	Presence of Bike Network	0.75	0.45	1.00	0.00
Collector	Number of Lane	2	0	2	2
	Lane Width (Left) (m)	3.50	0.41	4.45	3.2
	Lane Width (Right) (m)	3.45	0.43	4.45	3.2
	Road Width (m)	11.48	2.71	16.90	8.00
	Right of Way (m)	21.64	3.91	30.75	16.20
	Presence of Median	0.10	0.30	1.00	0.00
	Fixed Object Offset (Left) (m)	1.72	0.78	5.50	1.50
	Fixed Object Offset (Right) (m)	1.94	1.18	5.50	0.00
	Presence of Parking	0.71	0.46	1.00	0.00
	One Sided Parking	0.29	0.46	1.00	0.00
	Both Side Parking	0.43	0.50	1.00	0.00
	Presence of Bike Network	0.69	0.47	1.00	0.00
Arterial	Number of Lane	4.89	1.05	6.00	4.00
	Lane Width (Left) (m)	3.88	0.33	4.45	3.5
	Lane Width (Right) (m)	3.85	0.36	4.45	3.5
	Road Width (m)	23.57	4.78	30.60	18.90
	Right of Way (m)	38.72	5.76	46.70	31.50
	Presence of Median	1.00	0.00	1.00	1.00
	Fixed Object Offset (Left) (m)	2.00	0.00	2.00	2.00
	Fixed Object Offset (Right) (m)	2.00	0.00	2.00	2.00
	Presence of Parking	0.00	0.00	0.00	0.00
	One Sided Parking	0.00	0.00	0.00	0.00
	Both Side Parking	0.00	0.00	0.00	0.00
	Presence of Bike Network	0.22	0.44	1.00	0.00

3. METHODOLOGY

In 2010, the American Association of State Highway and Transportation Officials (AASHTO) published the HSM, which provides a comprehensive set of tools to analyze the safety performance of different roadway entities [9]. The HSM predictive method currently exists for three facility types: i) rural two-lane, two-way roads; ii) rural multilane highways; and iii) urban and suburban arterials. In the present analysis, the HSM predictive method for urban and suburban arterials was used to perform the safety analysis. Although this predictive method focuses only on urban arterial roads, the methodology can also be applied to local and collector roads (this will be discussed in greater detail later in this section). The predictive method for an individual roadway segment combines the base models, CMFs, and a calibration factor [9], each of which will be elaborated on in the next three sections.

3.1 Base Models

Base models are statistically derived regression models, also known as safety performance functions (SPFs), that predict roadway safety in terms of crash number, severity, and type. In this study, each SPF was developed with observed crash data for a set of similar sites. In the SPF, the estimated dependent variable is the predicted average crash frequency for a roadway segment under the base condition. The independent variables are the average annual daily traffic (AADT) and the road segment length. Each SPF also has an over-dispersion parameter, k , which provides an indication of the statistical reliability of the SPF. The closer that the over-dispersion parameter is to zero, the more statistically reliable the SPF becomes. For urban and suburban arterial road segments, there are five types of base models [9]:

- Two-lane undivided arterials (2U);
- Three-lane arterials (3T), including a centre two-way left-turn lane (TWLTL);
- Four-lane undivided arterials (4U);
- Four-lane divided arterials (4D), including either a raised or depressed median; and
- Five-lane arterials (5T), including a centre TWLTL.

According to the HSM, the SPF for multiple-vehicle non-driveway crashes is as follows [9]:

$$N_{base} = \exp(a + b \times \ln(AADT) + \ln(L) \qquad (1)$$

Where,

$AADT$ = Average annual daily traffic (vehicle/day) on the roadway segment;

L = Length of the roadway segment (miles); and

a, b = Regression coefficients.

Table 2 presents the values of the coefficients, a , b , and the over-dispersion parameter, k , of multiple-vehicle non-driveway crashes [9].

Table 2: Parameter Estimates of HSM Base Models [4]

Road Type	Coefficients		Over-dispersion Parameter (k)
	Intercept (a)	AADT (b)	
2U	-15.22	1.68	0.84
3T	-12.4	1.41	0.66
4U	-11.63	1.33	1.01
4D	-12.34	1.36	1.32
5T	-9.7	1.17	0.81

The base models were developed for a set of base conditions unique to each facility type. The HSM base conditions are lane width (12 ft), shoulder width (6 ft), shoulder type (paved), roadside hazard rating (three), driveway density (five driveways per mile), horizontal curvature (none), vertical curvature (none), centerline rumble strips (none), passing lanes (none), two-way left-turn lanes (none), lighting (none), automated speed enforcement (none), and grade level (0%) [9, 10, 11].

3.2 Crash Modification Factors (CMFs)

A CMF is a multiplicative factor used to reflect the expected change in safety performance associated with a corresponding change in highway design and (or) traffic control features [12]. CMFs are applied to SPFs when the characteristics of a road segment deviate from the base condition. For any feature that matches the base condition, the value of the CMF is equal to 1.0. If the expected outcome of applying a countermeasure, or in this case, a change in a certain street feature, is a reduction in predicted crashes, then the associated CMF would have a value less than 1.0. For an expected increase in crashes, the CMF would have a value greater than 1.0 [12, 10, 11, 13]. A CMF can be presented as a single numerical value or as functional forms, and can be developed by three techniques: i) observational before-after analysis; ii) cross-sectional analysis; and iii) expert judgment. CMFs are documented in the CMF Clearinghouse [14] and in other literature [15, 16]. In the present study, CMFs are expressed as a numerical value that reflects the anticipated change in safety, and are computed as the ratio between the expected number of collisions both with and without the design features, as presented in Eq. (2).

$$CMF = \frac{N_w}{N_{w/o}} \tag{2}$$

Where,

CMF = Crash modification factor;

N_w = Expected number of crashes with the proposed change; and

$N_{w/o}$ = Expected number of collisions without the proposed change.

CMFs are multiplied by the base prediction crashes (N_{base}), which adjusts the base predicted crash frequency to meet the actual conditions. Eq. (3) represents the predicted crashes for certain design features, which were not adjusted to the base condition.

$$N_{pred}(unadjusted) = N_{base} \times CMF_i \times \ldots \times CMF_n \times years \tag{3}$$

3.3 Calibration Factor

Crash frequency may vary substantially from one jurisdiction to another for a variety of reasons, including climate, driver populations, crash reporting thresholds, etc. [9]. Therefore, the predicted crashes ($N_{pred}(unadjusted)$) should be calibrated for application in each jurisdiction. To calibrate the predicted crashes, a calibration factor, C, should be included in the calculations.

$$N_{pred}(adjusted) = N_{base} \times (CMF_i \times \ldots \times CMF_n) \times years \times C \tag{4}$$

The HSM describes a method to develop the calibration process, which can be calculated using Eq.(5).

$$\text{Calibration Factor, } C = \frac{\sum observed\ crashes\ (N_{obs})}{\sum predicted\ crashes\ (N_{pred})} \tag{5}$$

Where,

N_{obs} = Observed number of crashes of similar sites; and

N_{pred} = Predicted number of crashes using base model and CMF of that sites.

The calibration factor should be developed using a certain number of sites for the same time period. To limit the influence of the observed annual fluctuations in the number of crashes, the analysis should extend over a study period of three to five years [9, 10, 13]. For this calibration analysis, the HSM suggests that at least 30 to 50 sites with at least 100 crashes per year should be included for each facility [9]. To avoid a site selection bias, the sites should be randomly selected, and then the number of crashes should be determined. Consequently, the dataset may include no-crash sites, as well as high-crash sites [9, 10, 13]. For the analysis, although the base models are for arterial roads only, the concept can be applied to cross section safety analysis.

It is worth mentioning that for most design drafts, the site type remains the same (e.g., the site types of designs 7-1 through designs 7-5 are four-lane divided arterials), as a result, the base prediction crashes (N_{base}) and the calibration factor, C , found in Eq. (4) remain constant for the same functional classification of roads. The only difference in the predicted number of crashes would then be due to the differences in on-road features (e.g., lane width, presence of parking, presence of a bike lane, etc.) and these differences are accounted for using the respective CMFs; therefore, the combined effects of all of the CMFs can be used to assess the safety performance of each cross section. The combined effects can be determined by multiplying all of the CMFs, which is the safety index, I , of the analyses.

Safety index, $I = CMF_i \times ... \times CMF_n$ *(6)*

An index with a value less than 1.0 corresponds to an expected reduction in crashes, and an index with a value greater than 1.0 corresponds to an expected increase in crashes.

3.4 CMF Calculation

The CMFs used to account for geometric and non-geometric road feature deviations of Complete Streets cross sections from the HSM base models are presented and discussed in this section.

3.4.1 Lane Width

The literature shows that an increase in lane width and lane number relatively reduces the associated collision risk, because more and wider lanes reduces not only the conflicting interactions between vehicles, but also the occurrence of risky maneuvers, such as aggressive overtaking and close car following [17, 18]. Therefore, the CMF for lane width on urban streets was derived by examining the relationship between lane width and safety performance using crash prediction models. The following function can be used to determine the CMF for lane width [12, 19]:

$$CMF_{LW} = \exp(-0.04(3.28\,W_L - 12)) \quad (7)$$

Where,

CMF_{LW} = Crash modification factor for lane width; and

W_L = Lane width in meters (m).

3.4.2 Presence of a Median

The presence of a median in a road segment was found to be significant in the reduction of both severe crashes and crash frequency [18, 20]. The median helps to prevent conflicts by separating opposing lanes of traffic and providing refuge for pedestrians and cyclists when crossing the road. The CMF for the presence of a raised median on an urban road is 0.61 [12, 21].

3.4.3 Presence of a Bike Lane

The literature shows that an on-street bike lane relatively increases the associated crash risk, because an on-street bike lane increases conflicting interactions between vehicles and bicycles [22]. Conversely, physically separated bike lanes, or "bicycle boulevards," prevent conflicts and reduce crash risk by separating vehicles and bicycles. Based on the literature, on an urban street, the CMF for an on-street bike lane is 1.05 [22], while the CMF for on-street bike lane markings is also 1.05 [22]. On the other hand, the CMF for a bicycle boulevard is 0.26 [23].

3.4.4 On-Street Parking

The CMF for on-street parking was adopted from the study by Bonneson et al. [9, 24] and is determined as:

$$CMF_{parking} = 1 + P_{pk} \times (f_{pk} - 1.0) \qquad (8)$$

Where,
$CMF_{parking}$ = Crash modification factor for the effect of on-street parking on total crashes;
f_{pk} = Factor from Table 12-19 in the HSM [9];
P_{pk} = Proportion of curb length with on-street parking (0.5 L_{pk} / L);
L_{pk} = Sum of curb length with on-street parking for both sides of the road combined (miles); and
L = Length of the roadway segment.

In the present analysis, it was assumed that for both-side on-street parking, the proportion of parking is 66%, and for one-side on-street parking, the proportion of parking is 33%.

3.4.5 Roadside Fixed Object

The CMF for roadside fixed objects was adopted from the study by Zegeer and Cynecki [9, 25]. The CMF was determined using the following equation:

$$CMF_{FD} = f_{offset} \times D_{fo} \times P_{fo} + (1.0 - P_{fo}) \qquad (9)$$

Where,
CMF_{FD} = Crash modification factor for the effect of roadside fixed objects on total crashes;
f_{offset} = Fixed object offset factor from Table 12-20 in HSM [9];
D_{fo} = Fixed object density (fixed object/mile) for both sides of road combined (for the analysis, 10 fixed objects/mile was assumed); and

P_{fo} = Fixed object collision as a proportion of total crashes from Table 12-21 in the HSM [9].

4. RESULTS AND DISCUSSIONS

This section summarizes the results of applying the procedures described in the preceding sections to assess the safety of each design alternative. The results show the safety indices for each of the designs, a low index (<1) indicates a lower safety risk, while a high index (>1) indicates a higher safety risk. The safety indices were obtained using the CMFs for lane width, presence of a median, presence of on-street parking, presence of a bike lane and roadside fixed object offset to identify the associated safety risk associated with each of the Complete Streets cross sections. The results of each alternative cross section for each functional road classification were compared with the base cross sections provided by the COE. It is worth pointing out that these results were based on many assumptions due to the limitations associated with applying the procedure; these limitations will be discussed in section five of this paper.

4.1 Local Roads

Figure 1 represents the indices of different local road cross sections. Interestingly, the indices are quite high and similar for most of the cross sections, which is obvious and intuitive for two key reasons. First and foremost, all of the local road cross sections are designed for residential land use with a street-oriented pattern. Therefore, the area design is pedestrian-biased with building entrances directly on the streets. Furthermore, a street-oriented design encourages on-street parking, which can calm roadway travel speeds and provide direct access to businesses and residences, and, hence, reduce the demand for off-street parking [7]. Consequently, most of the cross section designs have either one-side or both-side on-street parking. From a safety perspective, this can be beneficial, as on-street parking acts as a buffer to protect pedestrians and bicyclists on cycle tracks from motor vehicle traffic. Conversely, literature suggests that parking on one side of the road increases collisions by 34.3%, while parking on both sides of the road increases collisions by 24.9% (compared to no street parking) [26]. Therefore, CMFs for parking were quite high for all of the cross sections, except for the base condition. Secondly, most of the local road cross sections have a narrow road width (maximum 12.5m and minimum 8.0m), including parking (2.2m both side) and the bicycle lane (1.5m). These configurations impact the amount of space available for two-way vehicular traffic operations and often leads to single lane bi-directional traffic operation. Despite the fact that these configurations are suitable for a street-oriented design and operation, from a safety viewpoint, these will increase the probable safety risk, as literature shows an increase in lane width and lane number relatively reduces the associated collision risk [17, 18]. Therefore, the CMF for average lane width is quite high for most of the cross sections.

The results also reveal that design 5B-4 (the cross section illustrated in Figure 3) has the lowest index (0.458), while design 5B-9 has the highest (1.839). The difference between the base condition and design 5B-4 with respect to variation in CMF distribution is illustrated in Figure 2. In design 5B-4, the dominant feature is the presence of a bike lane. Because the bike lane is separated from the roadway (i.e., shared with the sidewalk), the safety risk is reduced compared to an on-street bike lane (i.e., shared with the roadway). The average fixed object offset has a comparatively low effect on the overall safety index. A narrow lane width and on-street parking increases the safety risk, while a separated bike lane reduces the safety risk of cross section 5B-4. Cross section 5B-9 has the highest safety risk due to a narrow lane width, both-side on-street parking and an on-street bike lane. The difference between the CMFs of the base condition and design 5B-9 for each roadway feature is illustrated in Figure 2.

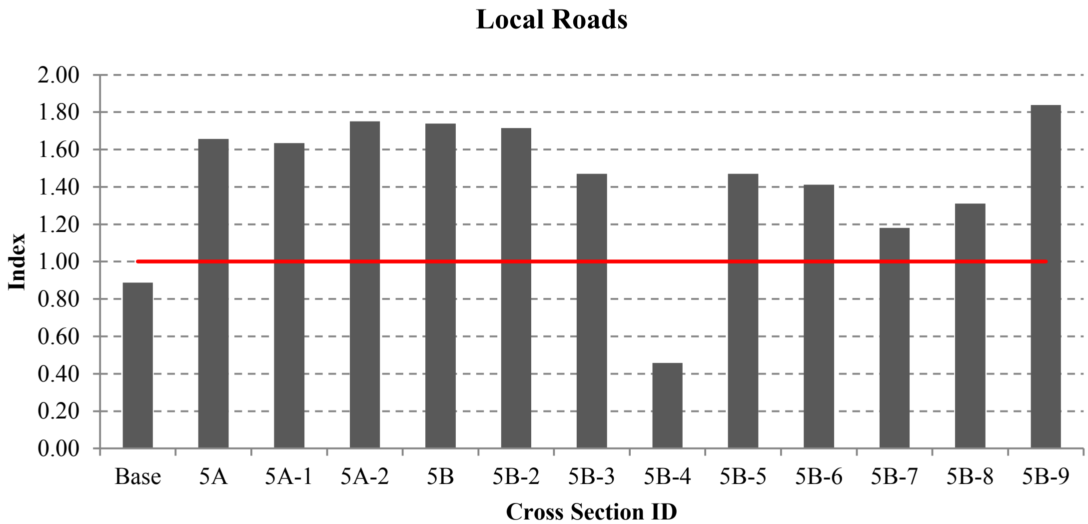


Figure 1: Safety Index of Different Cross Sections of Local Roads

Figure 2: Comparison of Base Condition and the Lowest (5B-4) and Highest (5B-9) Safety Risk Cross Sections Based on CMF Distribution for Local Roads

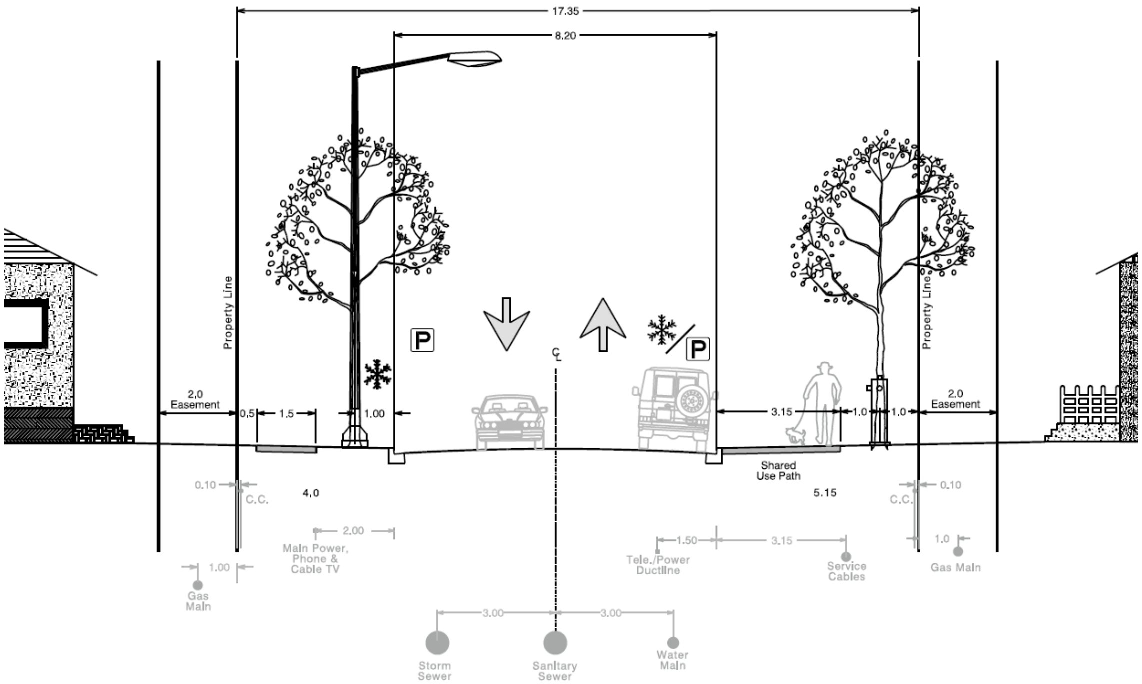


Figure 3: Lowest Safety Risk Cross Section (5B-4) of Local Roads

4.2 Collector Roads

Figure 4 represents the indices of different collector road cross sections. Due to the fact that the collector road cross sections are designed for different land uses (residential, commercial, and mixed use) with either street-oriented or non-street-oriented patterns, there is a wide variation in indices for different cross sections. Unlike street-oriented areas, non-street-oriented areas are generally biased towards automobile access and render the area less functional for pedestrians by separating buildings from one another and increasing walking distance. Regardless of land use, street-oriented and non-street-oriented patterns, design 1A to 2A-2 (Figure 4) have a high (<1) safety risk due to the presence of on-street parking (either one side or both side) and an on-street bike lane. All of the designs from 4B to 4B-4, except for design 4B-3, have a very low safety risk due to separated or buffered bike lanes or tracks. Furthermore, a non-street-oriented pattern with no on-street parking reduces the probable safety risk of these cross sections. Design 4B-3 has a cycle track in the middle of a two-lane two-way road, which may increase conflicting interactions between vehicles and bicycles, and, hence, increase the safety risk. Design 6 to 6-3 have more than two lanes with a raised median, which separates the oncoming traffic and reduces head on collisions. A separated bike lane further reduces the safety risk and leads to low safety indices (0.242) of these cross sections.

Design 4B-1 (Figure 6) has the lowest index (0.238), while design 3B-3 has the highest (1.94). The difference between the base condition and design 4B-1 in terms of CMF distribution is illustrated in Figure 5. In design 4B-1, the dominant feature is the presence of a bike lane. Because the bike lane is separated from the roadway (i.e., shared with the sidewalk), the safety risk is reduced compared to an on-street bike lane (i.e., shared with the roadway). Furthermore, there is no on-street parking, which reduces the safety risk. Cross section 3B-3 has the highest safety risk due to the presence of both-side on-street parking and an on-street bike lane. The difference in CMF distribution between the base condition and design 3B-3 is illustrated in Figure 5.

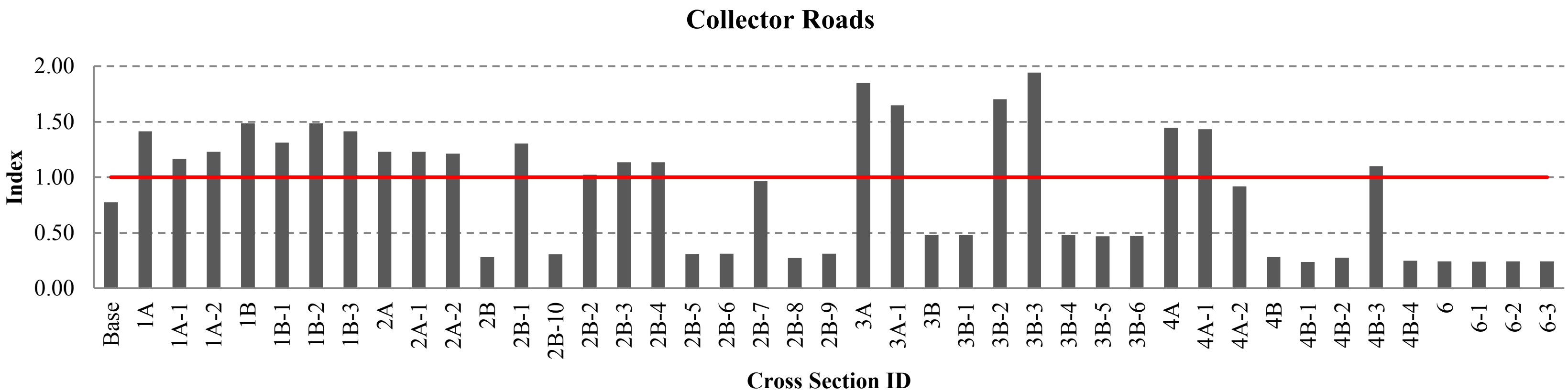
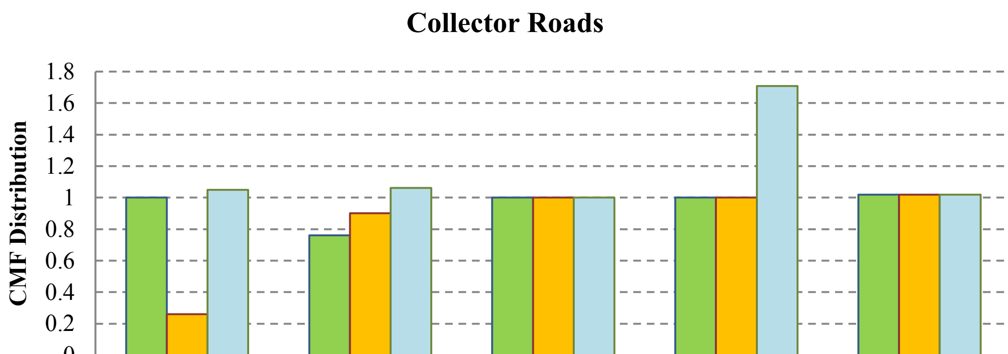


Figure 4: Safety Index of Different Cross Sections of Collector Roads



	BIKE	Average Lane Width	Median	Parking	Average Fixed Object
Base	1	0.760	1	1	1.019
4B-1	0.26	0.901	1	1	1.019
3B-3	1.05	1.062	1	1.709	1.019

Figure 5: Comparison of Base Condition and the Lowest (4B-1) and Highest (3B-3) Safety Risk Cross Sections Based on CMF Distribution for Collector Roads

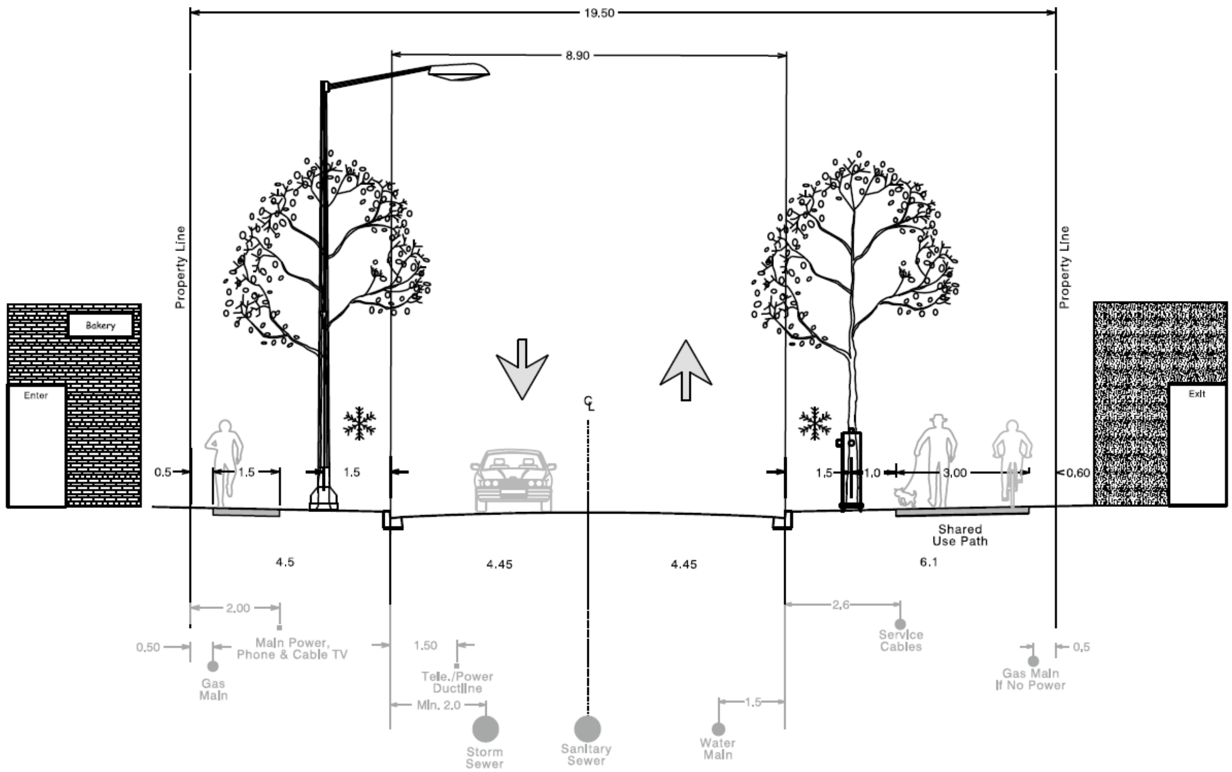


Figure 6: Lowest Safety Risk Cross Section (4B-1) of Collector Roads

4.3 Arterial Roads

All of the Complete Streets arterial cross sections are residential roads with a non-street-oriented pattern and are divided by a median, except for design 7-5. Figure 7 represents the indices of different arterial cross sections. Results show that design 7 (Figure 8) has the lowest index (0.1503), while design 7-5 has the highest (0.651). The indices are quite similar to the rest of the cross sections. In all of the cross sections, except for design 7-5, the dominant feature is the presence of a bike lane. Because the bike lane is separated from the roadway (i.e., shared with the sidewalk), the safety risk is reduced compared to an on-street bike lane (i.e., shared with the roadway). All of the cross sections have more than two lanes with a raised median, which helps to prevent conflicts by separating opposing lanes of traffic and providing refuge for pedestrians and bicyclists when crossing the road. Literature also suggests that the presence of a median decreases collisions by 52.7% [26]. A greater lane width and the absence of on-street parking also reduces the associated safety risk of these cross sections. Cross section 7-5 has the highest safety risk due to the presence of a two-way bike lane in the centre of the road, which increases conflicting interactions between vehicles and bicycles. The risk is even more severe on arterial roads, as the operating speed on arterials is quite high compared to local and collector roads.

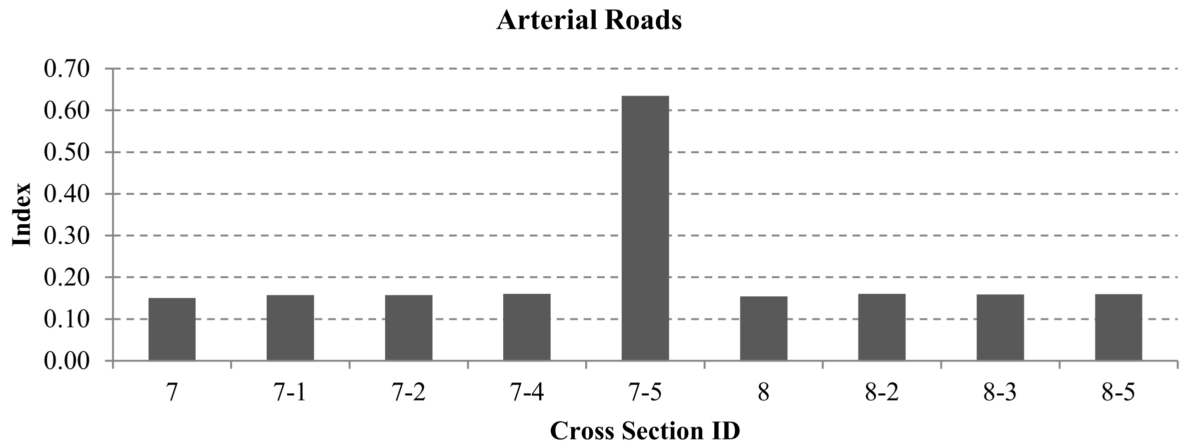


Figure 7: Safety Index of Different Cross Sections of Arterial Roads

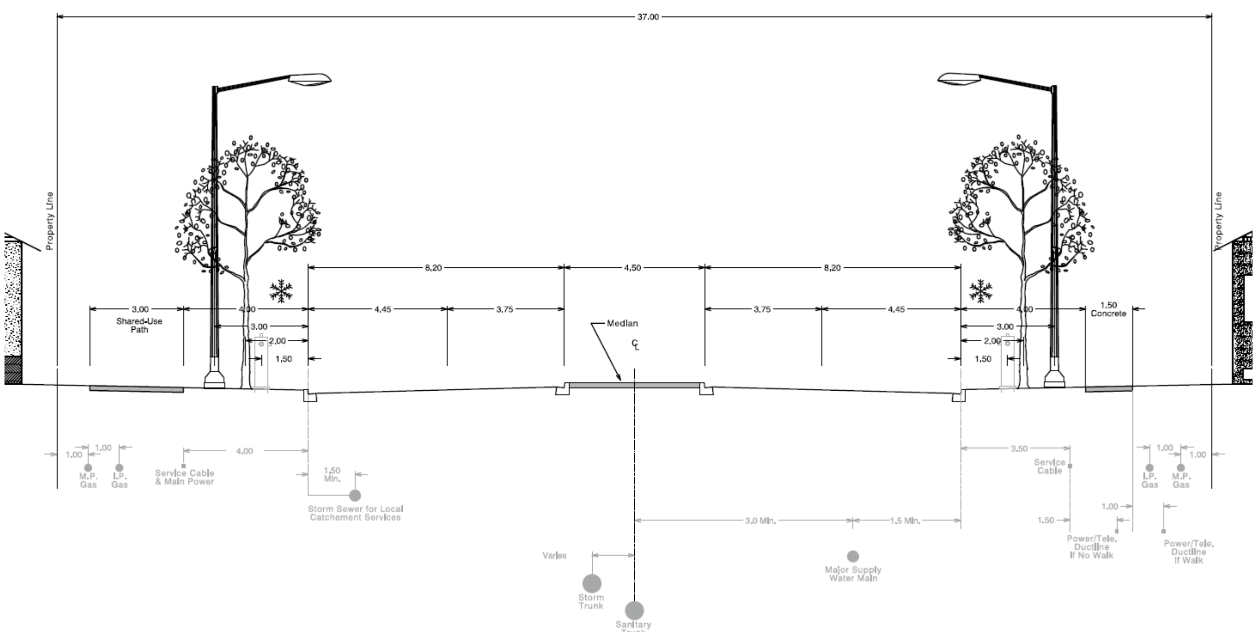


Figure 8: Lowest Safety Risk Cross Section (7) of Arterial Roads

5. ISSUES AND CHALLENGES

Throughout the assessment process of different Complete Streets cross sections, many issues and challenges were faced. In this section, the main challenges and issues related to applying the HSM predictive models for the safety assessment of Complete Streets cross sections are highlighted. First, the issues related to the availability of the HSM baseline models for different roadway facilities and site types are addressed; then, the difficulties and uncertainties experienced in finding and using appropriate CMFs to adjust the HSM baseline models are illustrated.

5.1 Lack of HSM Base Models

The adoption of Complete Streets policies is a growing trend all over Canada and draft cross sections have been proposed for the assessment for all road classes. The functional classification set by AASHTO divides roads into three different categories based on the degree of land access and the traffic characteristics. The definitions of each of those categories, namely, arterials, collectors and local roadways, are found in Table 3 [26].

Table 3: Functional Classification of Roads

Functional System	Services Provided
Arterial	Provides the highest level of service at the greatest speed for the longest uninterrupted distance, with some degree of access control.
Collector	Provides a less highly developed level of service at a lower speed for shorter distances by collecting traffic from local roads and connecting local roads with arterials.
Local	Consists of all roads not defined as arterials or collectors; primarily provides access to land with little or no through movement.

The HSM provides guidelines and baseline predictive models to estimate crashes for rural two-lane roads in Chapter 10, rural multilane roads in Chapter 11 and urban and suburban roads in Chapter 12 [9]. However, the urban and suburban roads covered in Chapter 12 include only those classified as arterials. This causes an issue when using the HSM predictive models to assess the safety of Complete Streets designs for other road classes. The residential nature of most collector and local roads actually indicates that a greater amount activity by vulnerable road users is expected on these roads, and, thus, more Complete Streets cross section designs should be developed for these road classes. Out of 63 Complete Streets cross sections drafted by the City of Edmonton, 42 were developed for collector roads and 12 for local roads, whereas, only nine different cross section design drafts were developed for arterials.

As a result of the lack of HSM base models for collector and local roads, cities and states have been working on developing their own SPFs. For instance, the Oregon Department of Transportation has been working on a research effort to develop SPFs for roadway types other than arterials in their region [27]. The City of Edmonton has also worked on developing SPFs for its collector roads [28]. The process to develop such models is extensive; hence, predictive models readily available in the HSM could be highly beneficial, particularly for regions where collision data is not available or not sufficient to develop SPFs. For instance, most of the collectors and locals are two-lane undivided roads; hence, the baseline model available for the two-lane undivided arterials could be used for the safety assessment of these road categories. However, any future version of HSM could expand its scope by incorporating the baseline models for collector and local roads.

As previously mentioned, HSM baseline prediction models in Chapter 12 are only available for the site types listed in section 4.1 of this paper. For urban arterials with more than five lanes, the HSM does not provide a base model in its current version. In the drafts proposed by the City of Edmonton, one of the arterial cross sections is a six-lane divided arterial. Due to the HSM limitation, the assessment of this design draft was not possible. This is another issue that could be considered when developing future versions of the HSM.

5.2 Collision Modification Factor-Related Issues

CMFs are a crucial element of the highway safety management process and are essential tools in adjusting the estimates of the HSM baseline SPFs. This section addresses the challenges faced with regards to finding and using CMFs to adjust the HSM baseline SPFs for the proposed Complete Streets design drafts.

Due to the multimodal nature of Complete Streets designs, the number of lanes, the width of lanes, the location of street lighting, the locations and presence of bike lanes, and many other features could differ significantly from one design proposal to another. This wide variation of street features among the different designs indicates that the difference between the proposed designs and the HSM baseline models was significant. Part of these changes can be accounted for using CMFs from both the HSM and the literature; however, for a significant portion of the designs, finding reliable CMFs was a challenge.

There is no doubt that the CMF clearinghouse [14] has been a tremendous resource for obtaining all sorts of CMFs. In addition to listing the value of the CMFs, the website [14] also summarizes all of the details of the study, such as the type of roadway and collision severities for which the CMF was developed. Moreover, the website's [14] sound rating system enables one to check the reliability of each of the CMFs. Nonetheless, there are some roadway features, such as different on-street parking locations (one side or both side), the presence of a sidewalk, and the street light orientations (as seen in Figure 9 and 10), for which reliable CMFs were not found in the literature.

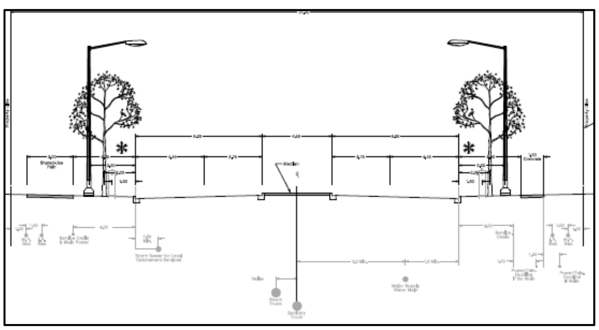


Figure 9: Street Lighting on Either Side of The Road

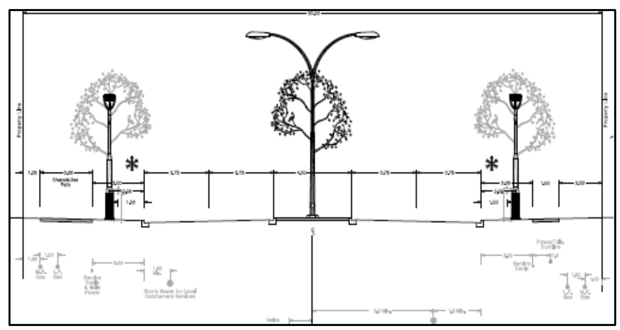


Figure 10: Street Lighting on the Median Only

Apart from the difficulty of finding reliable CMFs, when CMFs were found, in some cases the roadway category and collision severity did not match. For most CMFs found, the roadway category was either not specified or the CMFs were developed for arterials only. For instance, studies that developed CMFs for on-street bike lanes, bike lane markings, and bike lane boulevards did not specify the roadway category for which those CMFs were developed [22, 23]. Similarly, some CMFs focused on certain crash severities; for example, the study involving bike lane boulevards developed CMFs for only collisions of serious injury and minor injury severities [23].

The reliability of the CMFs that were found is also questionable due to the fact that most of them have been developed using data from other regions. This issue was also raised in previous literature [29]. However, it is still not clear how regional factors, such as geographic location, traffic volumes, and terrain, could affect the credibility of CMFs if used for a different region.

In addition to the difficulty in finding the appropriate CMFs and the question of their reliability, another issue arises from the proposed designs having a significant number of feature variations from the HSM baseline models. As a result, the number of CMFs required for adjusting the HSM base models in most cases exceeded three. The HSM advises against exceeding that number of CMFs, since combining several CMFs often results in magnified errors, and, hence, underestimation of the true number of collisions at a site [9]. In this paper, although CMFs were not found for some road features, five different CMFs were combined to find the safety indices for each design cross section, which, without doubt, reduces the reliability of the estimates made.

6. CONCLUSIONS & RECOMMENDATIONS

This paper demonstrated the use of HSM prediction models for the safety assessment of Complete Streets designs. The safety indices of each design were computed and the safest designs for each road category was recommended, namely, design 5B-4 for local roads, design 4B-1 for collector roads, and design 7 for arterials. However, these recommendations are based on several assumptions due to the issues faced during the assessment.

This paper also discussed the issues related to using the HSM predictive models in the safety assessment of Complete Streets designs. Some of these issues are related to the lack of HSM base models for certain roadway categories, such as urban collector and local roadways, and certain site types, such as six-lane divided arterials. Furthermore, the paper also illustrates potential issues related to using CMFs to adjust the HSM base models. The lack of reliable CMFs for some road features, such as the locations and orientation of on-street lighting, in the literature is quite evident; moreover, some CMFs have only been developed for a certain roadway category and (or) collision severity. Thus, assuming these CMFs are applicable for other roadway types and using them to predict collision reduction for other types of collisions reduces their reliability. The CMF consistency is also questionable when the CMFs are used for regions other than those for which they were developed due to a variation in factors, such as geographic location, traffic volumes, and terrain. Finally, due to the multimodal nature of Complete Streets designs, the number of CMFs used to adjust the HSM baseline models will most likely exceed three. The HSM advises against exceeding that limit, because it will most likely result in an overestimation of the CMF effects [9].

As a result, this study recommends that future researchers work on developing CMFs for certain features expected to dominate design proposals for Complete Streets. In addition, it is also important to consider methods to account for the errors caused by using several CMFs to adjust one base model for a Complete Streets design. Furthermore, it is clear that HSM baseline models for other roadway categories and site types must be considered in future versions of the HSM. Finally, future studies can also work on understanding the effects of using CMFs for regions other than those for which they have been developed.

REFERENCES

[1] Smart Growth America, "Smart Growth America: Making Neighborhoods Great Together," 2010. [Online]. Available: http://www.smartgrowthamerica.org/complete-streets/complete-streets-fundamentals/complete-streets-faq. [Accessed 4 January 2014].

[2] State of New Jersey DOT, "Complete Streets Policy," State of New Jersey DOT, New Jersey, USA, 2009.

[3] State of North Carolina DOT, "Complete Streets Policy," State of North Carolina DOT, North Carolina, USA, 2009.

[4] P. Jacobsen, "Safety in Numbers: More Walkers and Bicyclists, Safer Walking and Biking," *Injury*

Prevention, vol. 9, pp. 205-209, 2003.

[5] S. Seskin and L. Gordon-Koven, "The Best Complete Streets Policies of 2012," National Complete Streets Coalition and Smart Growth America, USA, 2013.

[6] Toronto Center for Active Transportation (TCAT), "Complete Streets for Canada," 2012. [Online]. Available: http://completestreetsforcanada.ca/case-studies. [Accessed 14 04 2014].

[7] City of Edmonton, "The Way We Move: Complete Streets Guidelines," Transportation Planning, City of Edmonton, Edmonton, Alberta, Canada, 2013.

[8] City of Edmonton, "The Way We Move: Transportation Master Plan," Transportation Planning, City of Edmonton, Edmonton, Alberta, Canada, 2009.

[9] American Association of State Highway and Transportation Officials (AASHTO), "Highway Safety Manual," AASHTO, Washington, DC, USA, 2010.

[10] B. K. Brimley, M. Saito and G. G. Schultz, "Calibration of Highway Safety Manual Safety Performance Function: Development of New Models for Rural Two-Lane Two-Way Highways," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2279, pp. 82-89, 2012.

[11] F. Martinelli, F. L. Torre and P. Vadi, "Calibration of the Highway Safety Manual's Accident Prediction Model for Italian Secondary Road Network," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2103, pp. 1-9, 2009.

[12] T. Sayed and P. d. Leur, "Collision Modification Factors For British Columbia," Engineering Branch, BC Ministry of Transportation & Infrastructure, British Columbia, Canada, 2008.

[13] F. Xie, K. Gladhill, K. K. Dixon and C. M. Monsere, "Calibration of Highway Safety Manual Predictive Models for Oregon State Highways," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2241, pp. 19-28, 2011.

[14] U.S. Department of Transportation Federal Highway Administration, "Crash Modification Factor Clearing House," FHWA, [Online]. Available: http://www.cmfclearinghouse.org/index.cfm. [Accessed 4 January 2014].

[15] Lehman Center for Transportation Research, Florida International University, "Update of Florida Crash Reduction Factors and Countermeasures to Improve the Development of District Safety Improvement Projects," State Safety Office, Florida Department of Transportation, Florida, USA, 2005.

[16] US Department of Transportation, Federal Highway Administration , "Toolbox of Countermeasures and Their Potential Effectiveness for Intersection Crashes," FHWA, USA, 2009.

[17] P. Greibe, "Accident prediction models for urban roads," *Accident Analysis and Prevention ,* vol. 35, p. 273–285, 2003.

[18] M. Ma, X. Yan, M. Abdel-Aty, H. Huang and X. Wang, "Safety Analysis of Urban Arterials Under Mixed-Traffic Patterns in Beijing," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2193, p. 105–115, 2010.

[19] M. A. Hadi, J. Aruldhas, L. F. Chow and J. A. Wattleworth, "Estimating safety effects of cross-section design for various highway types using negative binomial regression," *Transportation Research Record,* no. 1500, pp. 169-177, 1995.

[20] G. Berhanu, "Models Relating Traffic Safety with Road Environment and Traffic Flows on Arterial Roads in Addis Ababa," *Accident Analysis and Prevention,* vol. 36, no. 5, p. 697–704, 2004.

[21] R. Elvik and T. Vaa, The Handbook of Road Safety Measures, Oxford, United Kingdom: Elsevier, 2004.

[22] S. Jensen, "Bicycle Tracks and Lanes: a Before-After Study," in *TRB 87th Annual Meeting Compendium of Papers CD-ROM*, Washington, D.C., 2008.

[23] T. Nosal and L. Miranda-Moreno., "Cycle-tracks, bicycle lanes & on-street cycling in Montreal: a preliminary comparison of the cyclist injury risk," in *Presented at the 91st Annual Meeting of the Transportation Research Board*, Washington, DC, 2012.

[24] J. Bonneson, K. Zimmerman and K. Fitzpatrick, "Roadway Safety Design Synthesis," Texas Department of Transportation , Texas, USA, 2005.

[25] C. V. Zegeer and M. J. Cynecki, "Determination of Cost-Effective Roadway Treatments for Utility Pole Accidents," *Transportation Research Record,* no. 970, 1984.

[26] U.S. Department of Transportation Federal Highway Administration, FHWA-PD-97-062, 03 12 2012. [Online]. Available: http://www.fhwa.dot.gov/environment/publications/flexibility/. [Accessed 06 03 2014].

[27] Oregon DOT Research Unit, "Developing Safety Performance Functions for Oregon Collector, Local, and Low-Volume Roads," ODOT Research Unit, Oregon, 2013.

[28] S. B. Karim El-Basyouny and T. Islam, "Safety Performance Functions for Residential Collector Roads in the City of Edmonton," Office of Traffic Safety, City of Edmonton, Edmonton, Alberta, Canada, 2013.

[29] D. L. Carter, "Guidance for the Development and Application of Crash Modification Factors," University of North Carolina - Chapel Hill, North Carolina, USA, 2013.