A methodology to estimate the number of unsafe vehicle-cyclist passing events on urban arterials

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ABSTRACT

In this study interactions between motorized vehicles and bicycles were studied by analyzing the overtaking behavior of motorized vehicles when passing bicycles on urban arterials. A methodology is presented to estimate the number of 'unsafe' passing events on 4-lane urban arterials with no on-street bike lanes. A 'critical passing distance' is defined to classify expected passing maneuvers i.e. when a motorized vehicle overtakes a bicycle, into 'safe' and 'unsafe' passing events. The proposed method enables calculation of the expected number of 'unsafe passing' events based on the expected bicycle demand, road segment's length, AADT, speed limit, and traffic signal timing parameters. The 'critical passing distance' is an input parameter and can be set by the planner. Given the number of expected 'unsafe passing' events, and institutional safety objectives and standards in terms of acceptable risk levels for cyclists, transportation planning departments can use the proposed methodology to decide whether provision of a specific cycling facility is necessary for a given road segment.

1. Introduction

Availability of properly designed cycling facilities is essential for increasing the modal share of cycling. As an active transportation mode, cycling has essential health and environmental benefits (Oja et al., 2011; Grabow et al., 2012) while contributing significantly to sustainability of urban transportation. Despite the desire to increase the modal share of cycling, the use of motorized transportation modes is dominant in most North American urban and sub-urban areas. The absence of dedicated cycling facilities (e.g. on-street bike lanes) forces cyclists to share the road with motorized vehicles more frequently, and in turn, increases the potential for vehicle-cyclist collisions.

A study by the city of Toronto (City of Toronto, 2003) found that 12% of all collisions occurred when a motorized vehicle was overtaking a cyclist. It is anticipated that addressing the safety concerns associated with the use of bicycles on urban roads can significantly increase the modal share of cycling in urban areas. To prevent potential conflicts between cyclists and motorized vehicles, several jurisdictions in Canada and the US have implemented (or considering implementation of) a law which requires drivers to provide at least 1 m lateral clearance when overtaking a cyclist (Legislative Assembly of Ontario, 2010; Chapman, 2011), yet the effectiveness of such legislations are unknown. In current city planning practices the demand for cycling is accommodated through different cycling facilities which can be classified into four

categories:

i narrow lanes: are 2.75 m–3.65 m wide with no special provisions for cyclists. Cyclists share the lane with motorized vehicles and can either operate on the sides or use the entire lane,

ii wide lanes: are like narrow lanes except that they are 4 m–4.50 m wide,

iii dedicated on-street bike lanes: are usually 1 m–2 m wide on the sides of the travel lanes for motorized vehicle. The separation between the bike lane and the motorized vehicle lane is delineated using pavement markings, and

iv separated paths: include on-road bike lanes which are wider than 2 m, bike lanes separated with medians or curbs, raised bike lanes, bike lanes on the sidewalks and physically separated bike tracks.

Among these cycling facilities, only on-street bike lanes and separated paths provide dedicated space for cyclists. Construction of separated paths is costly and is subject to availability of required space (e.g. sufficient road width). On-street bike lanes are more practical and economical as they do not require any construction work and can be established quickly with minimal disruption for moving traffic. Provision of on-street bike lanes is a globally accepted practice aiming to eliminate potential conflicts between cyclists and motorized vehicles.

A recent study by Mehta et al. (2015) showed that when on-street

bike lanes are available vehicles tend to provide greater lateral clearance when overtaking cyclists on urban arterials. Thus, providing a safer environment for cyclists who share the road with vehicles. Likewise, a study conducted by Chuang et al. (2013) in Taiwan concluded that the presence of the bike lanes resulted in greater lateral distances between the cyclists and the passing vehicles. Nosal and Miranda-Moreno (2012) compared cyclist accident and injury data on streets with and without cycling facilities in Montreal. It was found that cyclists' injury rate on roads with bicycle facilities was significantly lower. A study conducted in Toronto (Ipsos Reid, 2009) concluded that only 31% of cyclists were comfortable sharing a road with motorized traffic in the absence of on-street bike lanes. Whereas, 72.5% of cyclists felt comfortable doing so when on-street bike lanes are present.

Despite the significance of on-street bike lanes for promoting the safety and convenience of cycling in urban areas, methods for establishing where they are needed are not yet fully established. Currently, the decision to provide an on-street bike lane on a specific road segment is based on its expected vehicle volumes (e.g. Average Annual Daily Traffic - AADT) and vehicle speeds (King, 2002). Thresholds for these volumes and speeds are generally determined based on 'engineering judgment' with no solid scientific evidence to prove their validity. For example, Ministry of Transportation Ontario (2013), recommends a three-step process to determine the need for a specific type of cycling facility (e.g. on-street bike lanes) on a given road. In the first step, the expected demand and speed on the roadway section is used to find the most suitable cycling facility using the provided design chart. In the next step, the most suitable cycling facility type is re-determined based on many site-specific criteria including AADT, speed, traffic volume, traffic safety records, etc. In the last step, the decision is finalized by comparing the analysis results in Steps 1 and 2. Similar guidelines can be found in other North American Jurisdictions (e.g. Minnesota Department of Transportation, 2007; Oregon Department of Transportation, 2011).

From the review of the existing guidelines for assessing the need for on-street bicycle lanes, it appears that:

1. there is lack of scientific evidence to support the validity of the existing guidelines,
2. there are inconsistencies in the existing procedures i.e. for a road segment with similar traffic and geometric conditions, on-street bike lanes may or may not be warranted based on the guidelines consulted, and
3. there is a necessity to develop a scientific approach to assess the need for on-street bike lanes considering predominant road traffic conditions and desired safety levels for the cyclists.

A methodology is presented in this paper to evaluate the need for providing on-street bicycle lanes or other cycling facilities on signalized urban arterials. A 'critical passing distance' is defined to classify expected passing maneuvers (i.e. when a motorized vehicle overtakes a bicycle), into 'safe' and 'unsafe' passing events. The proposed method enables calculation of the expected number of 'unsafe passing' events based on the expected bicycle demand, road segment's length, AADT, speed limit, and traffic signal timing parameters. The 'critical passing distance' is an input parameter and can be set by the planner. Given the number of expected 'unsafe passing' events, and institutional safety objectives and standards in terms of acceptable risk levels for cyclists, transportation planning departments can use the proposed methodology to decide whether provision of a specific cycling facility is necessary for a given road segment.

The rest of this paper is organized as follows. Section 2 presents a modeling approach to describe the interactions between motorized vehicles and cyclists during overtaking maneuvers. Empirical models are developed based on field observations and the models are expanded to consider additional input parameters such as AADT, speed limit, signal timing, and road segment length. Development of a methodology

to quantify the proportions of 'unsafe passing' events is described in Section 3. A stochastic modeling approach is presented to calculate the probability of 'unsafe passing' events which enables estimation of the expected number of 'unsafe passing' events for a given road segment considering projected bicycle demand levels. Model application is demonstrated in Section 4, and the last section describes the conclusions and discusses possible directions for future research.

2. Modeling vehicle-cyclist interactions

The focus of this study is on 4-lane urban arterials without on-street bike lanes (4LNB) and with on-street bike lanes (4LWB). However, the proposed methods can be used to develop similar models for other road categories such as 2-lane urban arterials. The following terms are frequently used in this article:

- *Passing event* is a maneuver during which a motorized vehicle overtakes a bicycle. The cyclist is assumed to be riding in the center (laterally) of the bike lane when a bike lane is present, or to the right-hand side of the curb lane when no bike lane is present.
- *Near lane passing* is a passing event in which the vehicle stays entirely within the near lane (curbside lane).
- *Far lane passing*: is a passing event in which the vehicle stays entirely within the far lane (median lane).
- *Encroachment passing* is a passing event in which the vehicle partially travels on the near lane and the far lane simultaneously.
- *Passing distance* is the lateral distance maintained between a motorized vehicle and a bicycle during a passing event.
- *Critical passing distance* is the minimum passing distance perceived as being safe (e.g. 1 m).
- *Safe passing* is a passing event with passing distance equal to or greater than the critical passing distance.
- *Unsafe passing* is a passing event which is not classified as 'safe'.
- *Restricted passing* is a passing event at which the motorized vehicle is restricted from making lane changes or encroaching into the adjacent lane due to the presence of other vehicles. Let h_1 and h_2 represent the time headway between the current passing vehicle in the near lane and the immediate leading and following vehicles in the far lane, respectively. If either h_1 or h_2 is less than or equal to a threshold value (e.g. 1.5 s), the passing event is considered 'restricted'.
- *Unrestricted passing* is a passing event which is not classified as 'restricted'.

2.1. Empirical observations

An instrumented bicycle was used to collect vehicle-cyclist interactions data including 5227 passing events observed on different urban road categories in Kitchener-Waterloo area in southern Ontario. As discussed in Mehta et al. (2015), vehicle-cyclist interactions data for this research was collected using a custom sensor array including an ultrasonic sensor, a GPS receiver, a microcontroller, and a data logger, which was installed on the back of the bicycle. For each passing maneuver, the sensor array could measure the lateral distance between the bike and passing vehicle, bicycle speed, and record location information and time of the passing event. The ultrasonic sensor was capable of taking measurements at every 100 ms with one-millimeter accuracy. In addition, passing maneuvers were recorded using a video camera mounted on the handlebar of the bicycle. Video recordings were used to calibrate the sensor array and later to investigate individual passing observations as needed. Collected data included 1895 passing events on 4LNB facilities and 2137 passing events on 4LWB facilities. Detailed analyses of the field observations are described in Mehta et al. (2015) which form the basis for the current study. Figs. 1a and 1b compare the cumulative probability (relative frequency) distributions of the observed passing distances on 4LNB and 4LWB facilities for restricted and
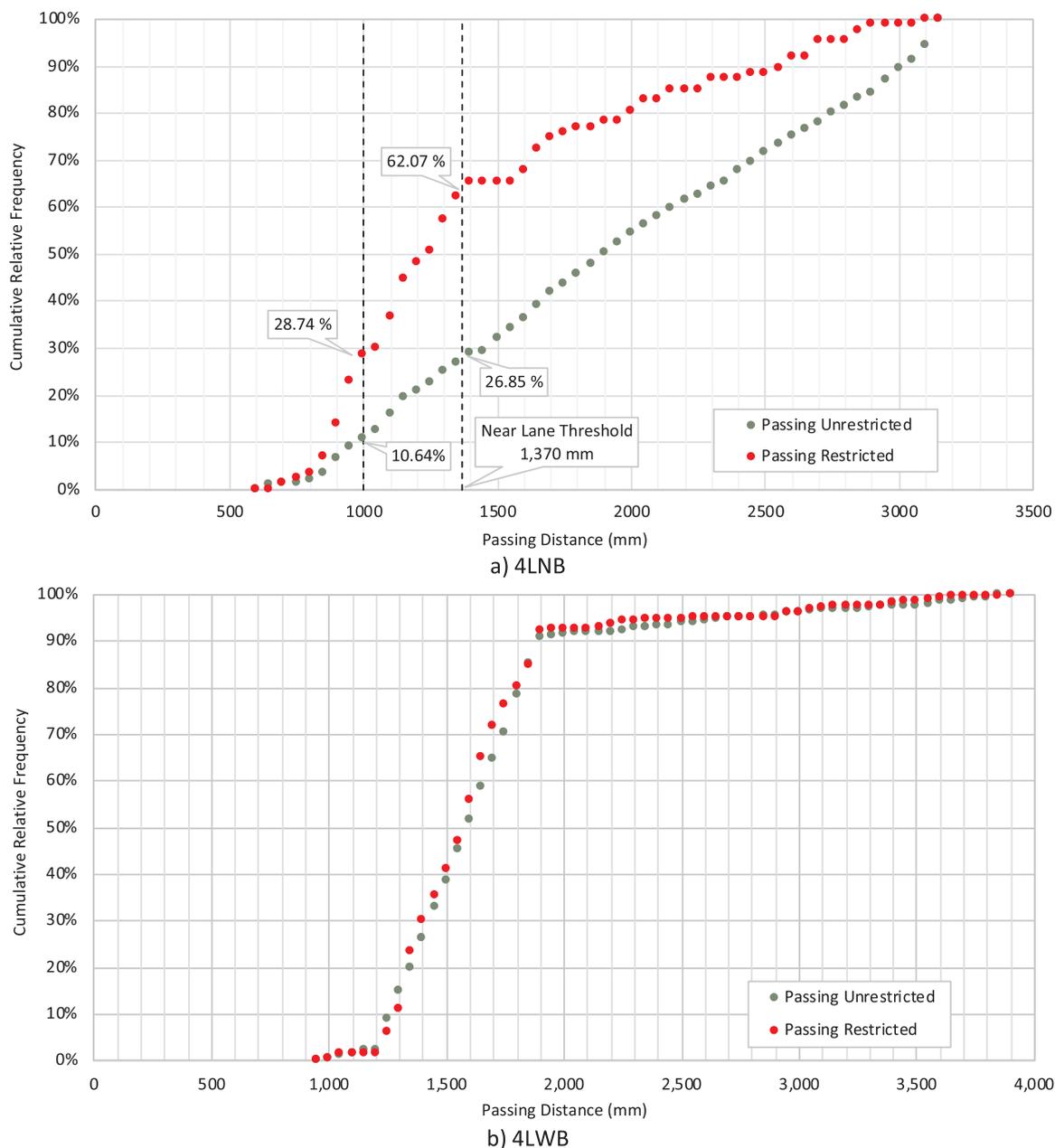
Fig. 1. Cumulative distribution of the observed passing distances (Mehta et al. (2015)).
a) Case I: Cycle time (C) = 60 s, green time (g) = 30 s (g/C = 0.5)
b) Case II: Cycle time (C) = 120 s, green time (g) = 60 s (g/C = 0.5)
c) Case III: Cycle time (C) = 60 s, green time (g) = 18 s (g/C = 0.3)

unrestricted passing events as presented in Mehta et al. (2015). It is observed that when on-street bike lanes are not available:

i drivers tend to provide smaller passing distances during restricted passing events,
ii a much higher proportion (29%) of restricted passing events were unsafe, compared to that of unrestricted passing events (11%), and
iii a much higher proportion of unrestricted passing events (73%) were encroachment or far lane passing compared to that of restricted passing events (38%).

In contrast, when on-street bike lanes are available, the distribution of the passing distances are almost identical for restricted and unrestricted passing events. The observations imply that in the absence of on-street bike lanes, drivers attempt to provide adequate passing distance by moving completely to the adjacent lane (i.e. far lane passing) or moving partially into the adjacent lane (i.e. encroachment passing) during passing events provided that they are not restricted from changing their travel lane due to the existence of other vehicles on the left lane. Yet, when on-street bike lanes are present, drivers on the near lane perceive that the provided lateral clearance is sufficient to pass the cyclists safely without needing to change lanes or encroach to the far lane, which demonstrates the significance and effectiveness of providing on-street bike lanes for improving traffic and cycling safety on 4LNB facilities.

2.2. Modeling the distribution of the passing distances

To model the distributions of the passing distances, empirical curves developed in Mehta et al. (2015) were used. Fig. 1a and b present the

Table 1
Statistical significance and performance indicators for passing distance models.

Equation	Variable	Coefficient	P(t-Stat)	R^2
(1a)	Intercept	549.57	3.298×10^{-5}	0.9852
	P_d	8216.70	0.038	
	P_d^2	155714	0.029	
(1b)	Intercept	722.48	4.879×10^{-39}	0.9979
	P_d	2172.50	1.156×10^{-31}	
	P_d^2	362.44	3.463×10^{-6}	
(2)	Intercept	606.91	5.283×10^{-22}	0.9955
	P_d	4879.90	0.007	
	P_d^2	−31742	0.039	
	P_d^3	110580	0.022	
	P_d^4	−195078	0.049	
	P_d^5	170,857	0.044	
	P_d^6	−57068	0.043	

cumulative probability of observing a specific passing distance on 4LNB and 4LWB facilities, respectively. The cumulative probability functions for 4LNB facilities in Fig. 1a were used to develop appropriate regression models. Eqs. (1) and (2) show the polynomial models developed for unrestricted and restricted passing events, respectively. P_d and d represent the cumulative probability and the passing distance (in millimeters), respectively.

$$d = \begin{cases} 155714 P_d^2 + 8216.7 P_d + 549.57 & 0 \le P_d \le 0.022 \ (a) \\ 362.44 P_d^2 + 2172.5 P_d + 722.48 & 0.022 < P_d \le 1 \ (b) \end{cases} \quad (1)$$

$$d = -57068 P_d^6 + 170857 P_d^5 - 195078 P_d^4 + 110580 P_d^3 - 31742 P_d^2 \\ + 4879.9 P_d + 606.91 \quad (2)$$

As presented in Table 1, developed models have high prediction power and estimated model parameters are statistically significant ($p = 0.05$).

### 2.3. Modeling the probability of restricted and unrestricted passing events

As discussed, for any passing event on 4LNB facilities, the passing distance is generally determined based on whether the passing event was restricted or unrestricted. Lane changing restriction for a vehicle on the near lane is imposed by traffic intensity and the presence of other vehicles in the far lane and these are essentially functions of vehicle platooning and platoon dispersion. Vehicle platoons on urban arterials are formed mainly because of traffic signal operations. The formation and the size of the platoons depend on traffic demand and signal timing parameters (e.g. duration of the red interval). Platoons disperse gradually as the vehicles are discharged from the signalized intersection and travel downstream. This dispersion rate is a function of the intersection capacity, road segment posted speed limit, and the traveled distance from the upstream signalized intersection. To model the impact of vehicle platooning on the possibility of restricted and unrestricted passing events, a simulation study was conducted using VISSIM Traffic Microsimulation software. A hypothetical 4LNB facility was modelled with an upstream signalized intersection. Only the through movement in one direction from the intersection was considered for analysis and the turning movements were disabled. Data collection points were established at 10-meter intervals on each lane downstream of the intersection. Cyclists were not modeled as the focus of the simulation study was on investigating how signal timing, section length, and AADT affect vehicle platooning and the probability of vehicles on the right lane being restricted from lane changing by the vehicles on the left lane, which determines whether a passing event is restricted or unrestricted if cyclists were present. The following conditions were controlled in the simulation model:

- *Section length* was set to 1 km since the distance between signalized intersections on most urban arterials is less than 1 km.
- *Posted speed limit* and *lane width* were set to 50 km/h and 3.65 m to be consistent with 4LNB facilities on which empirical data was collected (Mehta et al., 2015).
- *Vehicle composition* was determined by analyzing a sample of video recordings on different road categories at which empirical data was collected as per Mehta et al. (2015).
- *Traffic signal timing* scenarios were considered to demonstrate the impacts of traffic signal operations on platoon formation. The traffic signal was assumed to operate with a fixed-time two-phase timing plan. Different signal timing plans can be adopted to represent prevailing intersection operating conditions. For demonstration purpose, the following three signal timing cases were considered:
- Case I: Cycle time (C) = 60 s, green time (g) = 30 s (g/C = 0.5)
- Case II: Cycle time (C) = 120 s, green time (g) = 60 s (g/C = 0.5)
- Case III: Cycle time (C) = 60 s, green time (g) = 18 s (g/C = 0.3)
- *Saturation flow rate* (s) was set to 1900 vehicles per hour per lane.
- *Traffic demand* was determined based on intersection's v/c (demand to capacity) ratio. For each signal timing case, 10 different traffic demand scenarios were evaluated based on different v/c ratios (v/c = 0.1–1.0 in 0.1 increments). For each scenario, intersection capacity was estimated using Eq. (3) considering the number of lanes in one direction ($n = 2$), and then traffic demand was calculated by multiplying intersection capacity by desired v/c ratio. To be consistent with existing cycling facility design guidelines, the demand was converted to AADT for further analyses using Eq. (4) based on the assumption that the demand represents the peak-hour flow rate i.e. directional design hourly volume (DDHV). In Eq. (4), D represents the section's proportion of peak-hour traffic in peak direction which is assumed to be 50% of the total traffic in both directions in the peak-hour ($D = 0.5$). The k factor represents the portion of AADT that travels through the section in the peak-hour. Highway Capacity Manual (Transportation Research Board, 2016) recommends $k = 0.1$ for urban arterials. Different values can be assumed for D and k based on peak-hour traffic characteristics and road category.

$$c = s \times n \times \frac{g}{C} \quad (3)$$

$$AADT = \frac{DDHV}{k \times D} \quad (4)$$

For each combination of demand scenarios and signal timing cases, 10 simulation runs were conducted using different random seeds. It should be noted that the required number of simulation runs is a function of confidence level, acceptable error, and standard deviation of the parameter being estimated (i.e. the proportion of restricted passing events) which can be estimated using statistical methods for sampling. The duration of each simulation run was one hour (peak-hour analysis). At each simulation run the proportion of possible restricted passing events for the vehicles traveling in the near lane was calculated at every 10-meter interval on the section based on the headway criteria defined for restricted passing events. Fig. 2 presents the results for all combinations of demand scenarios and signal timing cases. The horizontal axis shows the distance from the upstream intersection in meters (x) and the vertical axis shows the proportion of possible restricted passing events (y) observed in 10 simulation runs for each demand scenario and signal timing cases. The percentage of possible unrestricted passing events for any location along the study section is the complement of the percentage of possible restricted passing events at the same location (i.e. 1-y). The results show as the section length increases, the proportion of restricted passing events decreases, which support the notion that the type of passing event (restricted vs. unrestricted) is a function of platoon dispersion. As the length of the section increases, vehicles in a platoon become less concentrated and consequently, a higher number
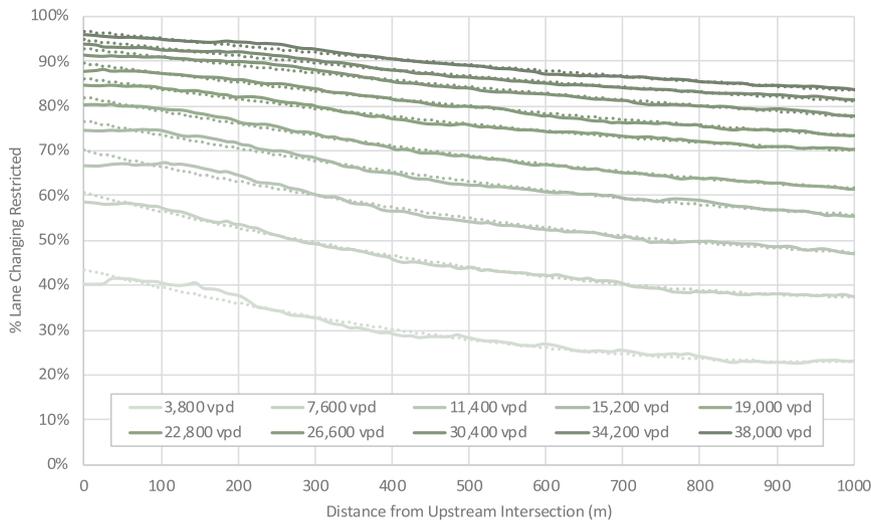
a) Case I: Cycle time (*C*) = 60 sec, green time (*g*) = 30 sec (*g/C* = 0.5)
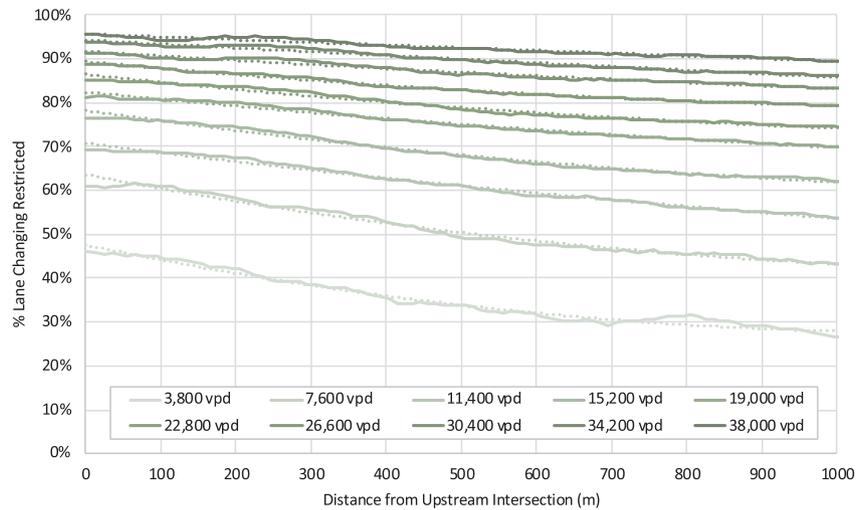
b) Case II: Cycle time (*C*) = 120 sec, green time (*g*) = 60 sec (*g/C* = 0.5)
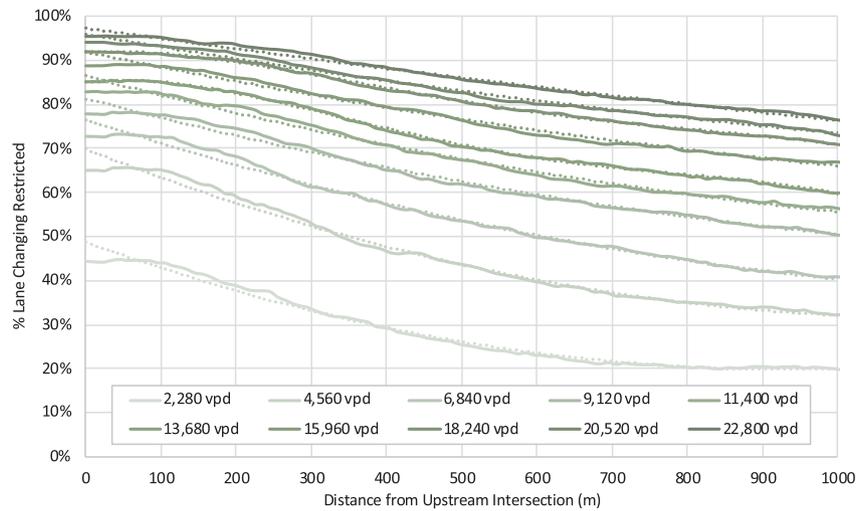
c) Case III: Cycle time (C) = 60 sec, green time (g) = 18 sec (g/C = 0.3)

Fig. 2. Possibility of restricted passing events as function of distance from upstream intersection.

of unrestricted passing events are expected. Also, as expected, as the traffic volume increases, the proportion of restricted passing events also increases.

Based on the curves presented in Fig. 2, linear and second order polynomial regression models were evaluated to estimate the percentage of restricted passing events as function of the distance from
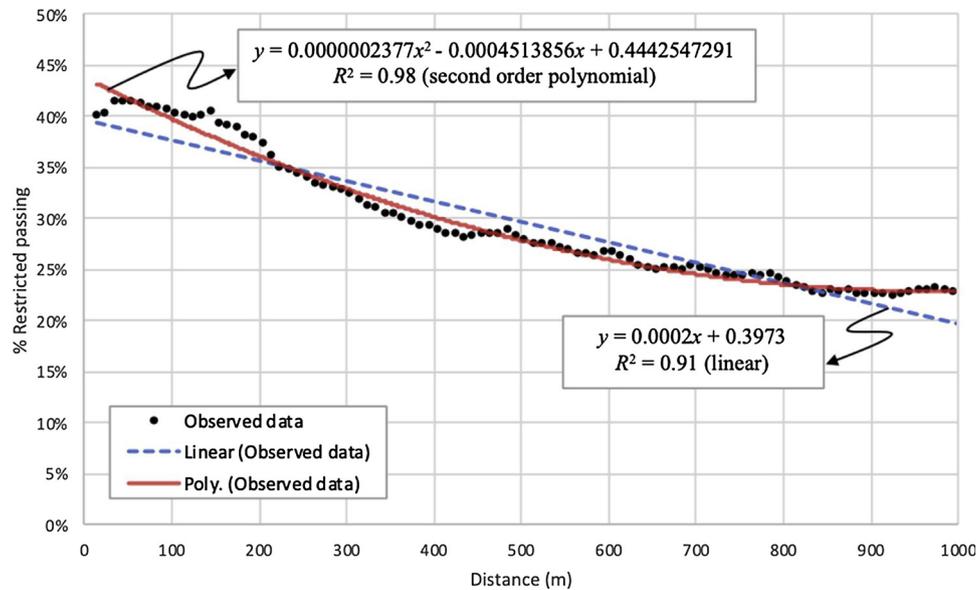
Fig. 3. Regression models to estimate the percentage of restricted passing events as function of the distance from upstream intersection for Case I, v/c ratio of 0.1.

upstream intersection. Second order polynomial models were selected due to their better performance (higher R^2). Fig. 3 shows a detailed example for Case I, v/c ratio of 0.1. In Fig. 3, y and x represent the proportion of restricted passing events, and the distance from upstream intersection (in meters), respectively. Similar models were developed for all combinations of demand scenarios and signal timing cases and used for subsequent analyses.

3. Quantifying unsafe passing events

One of the main objectives of this study is to develop a methodology to quantify the expected number of unsafe passing events on 4LNB facilities. The developed models described in the preceding section are used to establish a stochastic approach to estimate the number of expected unsafe passing events as described in this section.

3.1. Stochastic modeling of the probability of unsafe passing events

It was shown that the section length has significant impact on the type of the passing events (restricted vs. unrestricted) as well as the distribution of the passing distances. Thus, it is expected that the probability of unsafe passing events is greatly influenced by the section length. This section describes the development of models for estimating the probability of unsafe passing events.

We begin by defining a set of 600 scenarios that represent combinations of different traffic demands, signal timings, and roadway segment lengths for a 4LNB section. Twenty different section lengths scenarios (from 50 m to 1000 m in 50 m increments) were considered. For each section length scenario, 10 different traffic demand scenarios (determined using the v/c ratios from 0.1 to 1.0 in 0.1 increments and converted to AADT) and three signal timing cases (as described in preceding section) were considered.

The following steps describe the stochastic approach used for estimating the probability of unsafe passing events on a given 4LNB section:

- *Step 1*: A combination of length, demand scenario, and signal timing case is assigned to the assumed study section (i.e. one of the 600 scenarios defined above).
- *Step 2*: A passing location is selected for a potential passing event along the study section. It is assumed that passing events are distributed uniformly and can take place on every one-centimeter

interval along the section length. For a selected passing location, a passing distance will be assigned stochastically following steps 3 through 5.
- *Step 3*: For a given passing location, the probability that the potential passing event will be restricted is calculated using the models developed in Section 2.3 (e.g. second order polynomial regression model in Fig. 3) considering the passing location, traffic demand, and signal timing cases.
- *Step 4*: A passing event can have two outcomes i.e. restricted or unrestricted. It is assumed that the passing event type is distributed based on the Binomial distribution. Given the probability of having a restricted passing event calculated in Step 3, binomial sampling method (number of trials, $n = 1$) is used to randomly determine whether the passing event is restricted (pass) or unrestricted (fail).
- *Step 5*: Once the type of the passing event is determined, Monte Carlo sampling technique is used to assign a random passing distance using Eqs. (1) and (2) for unrestricted and restricted passing events, respectively. The cumulative probability of observing a specific passing distance, i.e. P_d in Eqs. (1) and (2) is determined by generating a random number between 0 and 1 based on uniform distribution. For unrestricted passing events, if the generated random number is equal to or less than 0.022, Equation (1a) is used. Otherwise Equation (1b) is used.
- *Step 6*: Steps 2 through 5 are repeated until all feasible passing locations along the section are evaluated. For example, for a 700 m long section, the above steps are repeated 70,000 ($700 \times 100 = 70,000$) times.
- *Step 7*: Once the passing distances are estimated at each one-centimeter interval, the distribution of the passing distances is evaluated and the cumulative probability associated with the passing distance of 1000 mm (critical passing distance) is found along the study section.
- *Step 8*: Steps 1 through 7 are repeated 10 times. The arithmetic mean of the resulting 10 probability values associated with the passing distance of 1000 mm was calculated and used as the final value for the probability of unsafe passing for the given scenario.
- *Step 9*: Steps 1 through 8 are repeated for all 600 scenarios (i.e. combinations of section length, traffic demand and signal timing).

The analysis was performed for all section lengths scenarios (from 50 m to 1000 m in 50 m increments) and the probabilities for unsafe passing events (P_u) were estimated considering section lengths (l),
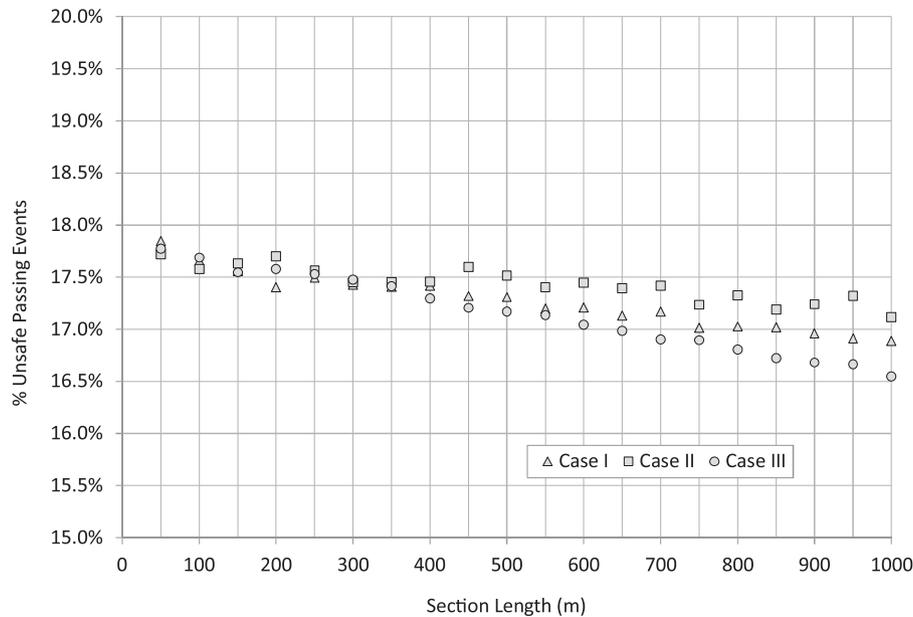
Fig. 4. The relationship between section length and the probability of unsafe passing for v/c ratio of 0.9 considering all signal timing cases.

different traffic demand scenarios (as function of AADT), and signal timing cases.

The relationship between section length and the probability of unsafe passing is shown in Fig. 4 for v/c = 0.9. From these results we make the following observations:

1. The maximum probability for unsafe passing events is observed on the shortest sections and it decreases as section length increases. This result is expected because a passing event is more likely to be unsafe when it is restricted (versus unrestricted), and passing vehicles are more likely to be restricted when they are part of a dense platoon. Platoons are most dense when they have just discharged and tend to disperse (become less dense) as they travel downstream. The relationship between the probability of observing unsafe passing events and section length can be approximated using linear functions for all three signal cases.

2. For short section lengths, there is little difference between the probabilities of unsafe passing events for three signal cases. However, for longer section lengths, the three signal cases demonstrate different results, with Case III having smaller probabilities of unsafe passing events. For the section length of 1000 m, the probabilities of observing unsafe passing events are 16.9%, 17.1% and 16.5% for signal timing Cases I, II, and III.

The relationship between AADT and the probability of unsafe passing is illustrated in Fig. 5 for a 700 m long section. It is observed that the probability of unsafe passing events is proportional to AADT. For a higher AADT, bigger platoons are formed. Thus, for the same section length, the probability of unsafe passing events increases as the AADT increases. Additionally, it can be observed that for the same AADT, the probability of observing an unsafe passing event is significantly higher when signal timing Case III is implemented. This is because the intersection capacity for Case III is smaller than for Cases I and II. Therefore, for a given AADT, bigger queues will be formed upstream of the signal as compared to when signal timing Cases I and II are implemented. The bigger the platoon, the longer it takes for it to disperse as vehicles travel further downstream. Thus, the probability of observing unsafe passing events is higher for signal timing Case III.

Based on the analysis results described in steps 1–9, continuous regression models can be developed based on the estimated probabilities for each combination of section length and traffic demand. Eqs.

(5)–(7) represent the models developed for signal timing cases I, II, and III, respectively. The models imply that the probability of unsafe passing events is directly related to AADT and inversely related to the section length. The coefficients are all statistically significant as noted in Table 2.

$$P_u = 0.126 + \frac{1.66(AADT)}{1,000,000} - \frac{1.3(l)}{100,000} \tag{5}$$

$$P_u = 0.130 + \frac{1.49(AADT)}{1,000,000} - \frac{0.859(l)}{100,000} \tag{6}$$

$$P_u = 0.134 + \frac{2.38(AADT)}{1,000,000} - \frac{1.8(l)}{100,000} \tag{7}$$

3.2. Estimation of the expected number of unsafe passing events

The expected number of unsafe passing events on a 4LNB section (N_{cr}) can be calculated using Eq. (8) given the probability of unsafe passing events (P_u) and the total number of expected passing events initiated on the near lane (N_t). Interactions between cyclists and the vehicles traveling on the far lane are not considered because their corresponding passing distance is always greater than the critical passing distance (e.g. 1 m). Eqs. (5)–(7) were presented earlier to calculate the probability of unsafe passing events for a given 4LNB section as a function of its AADT and length considering different signal timing cases.

$$N_{cr} = P_u \times N_t \tag{8}$$

To use Eq. (8) it is necessary to calculate the total number of expected passing events initiated on the near lane (N_t), which is explained in this section.

The space-time diagram in Fig. 6 illustrates a passing event on a 4LNB section with the length of x. A cyclist travelling at a constant speed of v_b takes time t_b to traverse the entire section. To travel through the same section, a vehicle travelling at a constant speed of v_v requires time t_v. Therefore, the last vehicle that can overtake the cyclist on this section should enter the section no later than time t_b-t_v. Any vehicle entering the section after this time will not be able to overtake the cyclist on this section. Thus, the total number of expected passing events per bicycle trip initiated on the near lane (N_b) can be estimated using Eq. (9) given the average headway of the vehicles traveling in the
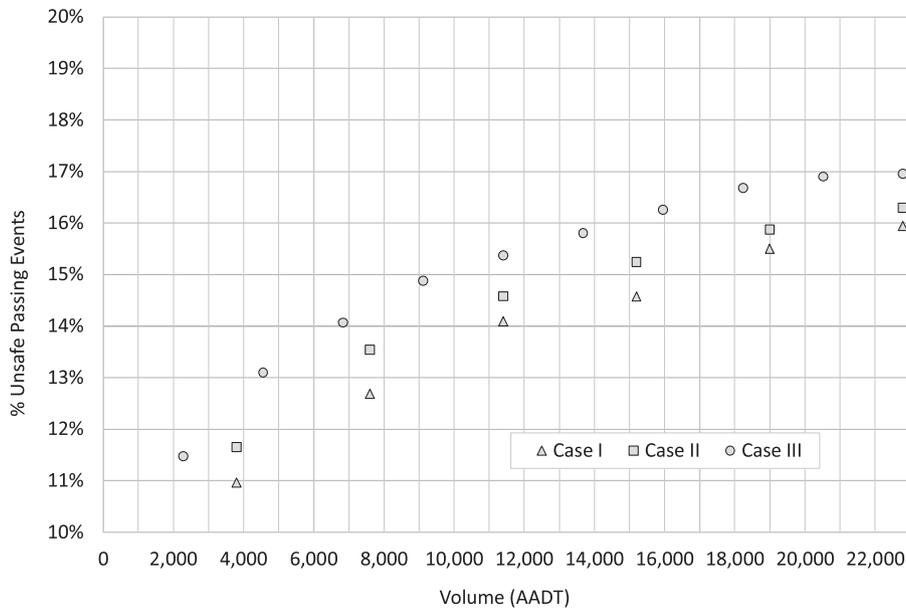
Fig. 5. The relationship between AADT and the probability of unsafe passing for section length 700 m considering all signal timing cases.

Table 2
Statistical significance and performance indicators for models to estimate the probabilities of unsafe passing.

Signal timing Case	Variable	Coefficients	P (t > t-Stat)	R^2
I	Intercept	0.126	1.8×10^{-172}	
	AADT	1.66×10^{-6}	2.3×10^{-99}	0.90
	Section Length (m)	-1.3×10^{-5}	2.05×10^{-14}	
II	Intercept	0.130	10^{-184}	
	AADT	1.49×10^{-6}	1.09×10^{-99}	0.90
	Section Length (m)	-8.59×10^{-6}	1.62×10^{-9}	
III	Intercept	0.134	1.3×10^{-185}	
	AADT	2.38×10^{-6}	9.22×10^{-95}	0.93
	Section Length (m)	-1.8×10^{-5}	1.08×10^{-27}	

near lane (h).

$$N_b = \frac{t_b - t_v}{h} \tag{9}$$

The average headway in Eq. (9) is a function of traffic demand on the near lane. Traffic demand is represented by the section's AADT as explained earlier. Given α as the lane utilization factor representing the proportion of total traffic in one direction that travels on the near lane, the average headway (h in sec) can be estimated using Eq. (10).

$$h = \frac{3600}{\alpha \times DDHV} \tag{10}$$

It is assumed that $\alpha = 0.5$, which means the traffic is equally distributed across the lanes. The directional design hourly volume (*DDHV*) is related to the section's AADT and can be estimated by solving Eq. (4)
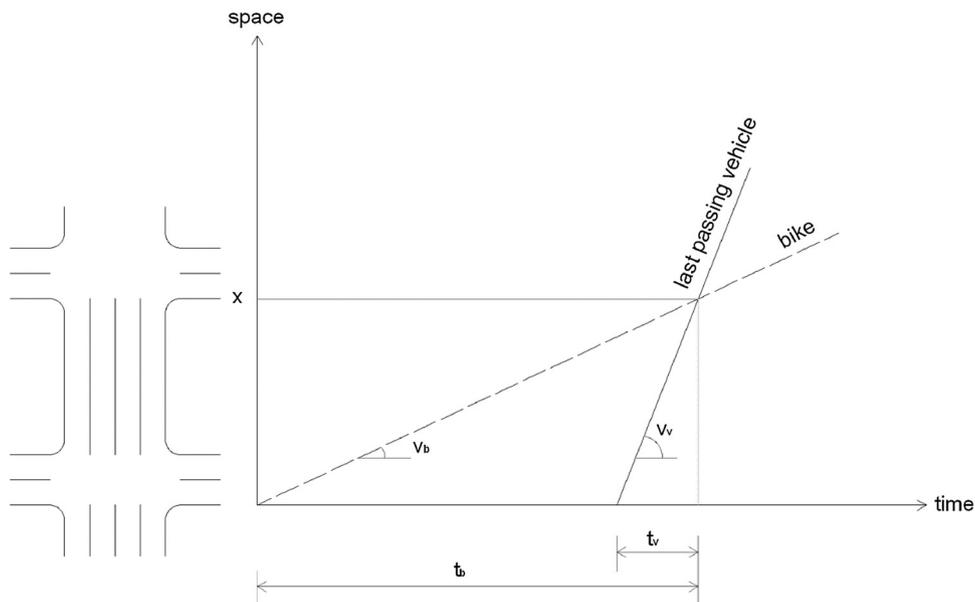

Fig. 6. Representation of a passing event on a 4LNB section.
a) Signal timing case I
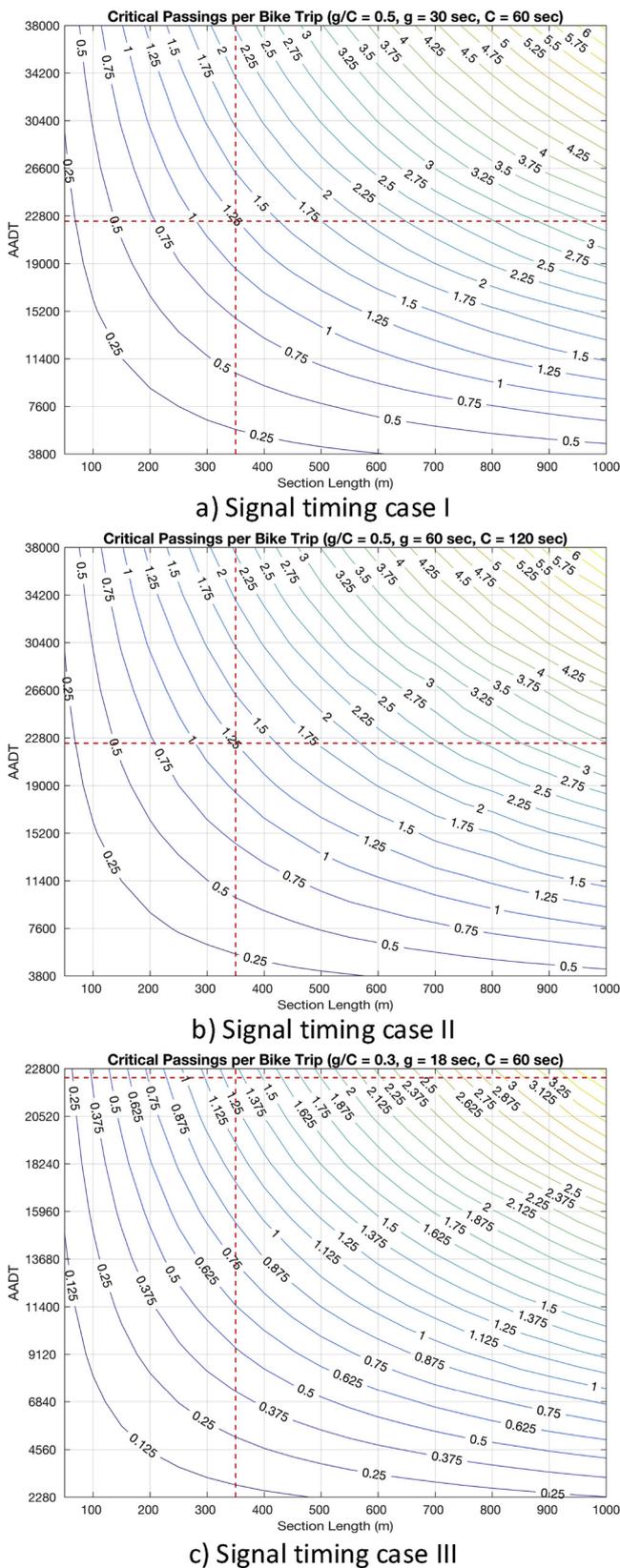b) Signal timing case II
c) Signal timing case III

Fig. 7. Expected number of unsafe passing events per bicycle trip per hour.

for *DDHV*.

Finally, the total number of expected passing events initiated on the near lane (N_t) can be estimated using Eq. (11), where q_b is an input design parameter representing the expected hourly bicycle demand.

$$N_t = q_b \times N_b \tag{11}$$

For this analysis, it is necessary to assume values for the speed of vehicles (v_v) and cyclists (v_b). In this analysis, values of 50 km/h and 17 km/h have been assumed for speeds of vehicles and cyclists, respectively.

Although the procedures for estimating the total number of expected passing events per bicycle trip (N_b) per hour are straightforward, they are time intensive. Alternatively, Fig. 7 can be used to estimate N_b considering signal-timing configurations in the peak-hour. For example, using Fig. 7c for a 1000-meter 4LNB section with expected AADT of 9120 vehicles and signal timing configuration of Case III, the expected number of unsafe passing events per bike trip per hour is 1.22. If in the peak-hour, 100 bikes are expected to travel through this section, the total number of unsafe passing events will be 122 (1.22 × 100). It is important to note that the diagrams in Fig. 7 are based on the critical passing distance of 1000 mm. Similar figures can be produced for other values of critical passing distance.

The number of estimated unsafe passing events per bike trip per hour (n_{cr}) can be estimated using Eq. (12), which was derived by combining Eqs. (4) and (8)–(11). The hourly bicycle demand in Eq. (11) was set to $q_b = 1$ to derive Eq. (12).

$$n_{cr} = \left[\frac{(\frac{1}{v_b} - \frac{1}{v_v}) \times k \times D \times \propto}{1000} \right](P_u \times l \times AADT) \tag{12}$$

The first term (the term in the square brackets) in Eq. (12) is a constant value. Thus, n_{cr} is proportional to P_u, section length and AADT. P_u was modeled as a linear function of section length and AADT as described in Eqs. (5)–(7). As a result, the relationship between n_{cr} and section length and AADT is nonlinear (e.g. polynomial function).

4. Application of the proposed methodology

The proposed methodology to estimate the number of unsafe passing events per bike trip per hour was applied to a section of University Ave E in Waterloo, Ontario, which is located between Regina St N and Weber St N as shown in Fig. 8. This section is a 4LNB facility with narrow lanes (lane width = 3.65 m). The length of the section is 350 m and the posted speed limit is 50 km/h. The AADT on this section, which was obtained from the Region of Waterloo (Transportation and Environmental Services) for the year 2012, was 22,375 vehicles per day. For signal-timing configuration at upstream intersection (i.e. at Regina St N and University Ave E), the three signal-timing cases used earlier in the analyses were considered. The diagrams presented in Fig. 7 were used to estimate the number of unsafe passing events per bike trip per hour for this section. As shown in Fig. 7, the intersection points of the dashed lines representing section length and AADT indicate 1.25, 1.25 and 1.32 unsafe passing events per bike trip per hour on this section for the three signal timing cases, respectively.

Fig. 9 shows variations of the estimated number of unsafe passing events per bicycle trip per hour (n_{cr}) as function of section length for the study section (AADT = 22,375 vehicle per day) considering all signal timing cases. Polynomial trend-lines were fitted to data points to highlight the variations. It can be observed that n_{cr} is larger for signal timing Case III which is due to formation of bigger platoons at the upstream intersection as intersection capacity for signal timing Case III is much smaller than for the other two cases. For all three signal timing cases, n_{cr} increases as the section becomes longer, which is expected as cyclists are exposed to more frequent overtaking events along longer sections.

Ontario Traffic Manual Book 18 (Ministry of Transportation Ontario, 2013) and Oregon Bicycle and Pedestrian Design Guide (Oregon Department of Transportation, 2011) were also used to determine the preferred cycling facility on this section. Ministry of Transportation Ontario (2013) guidelines indicate that the provided
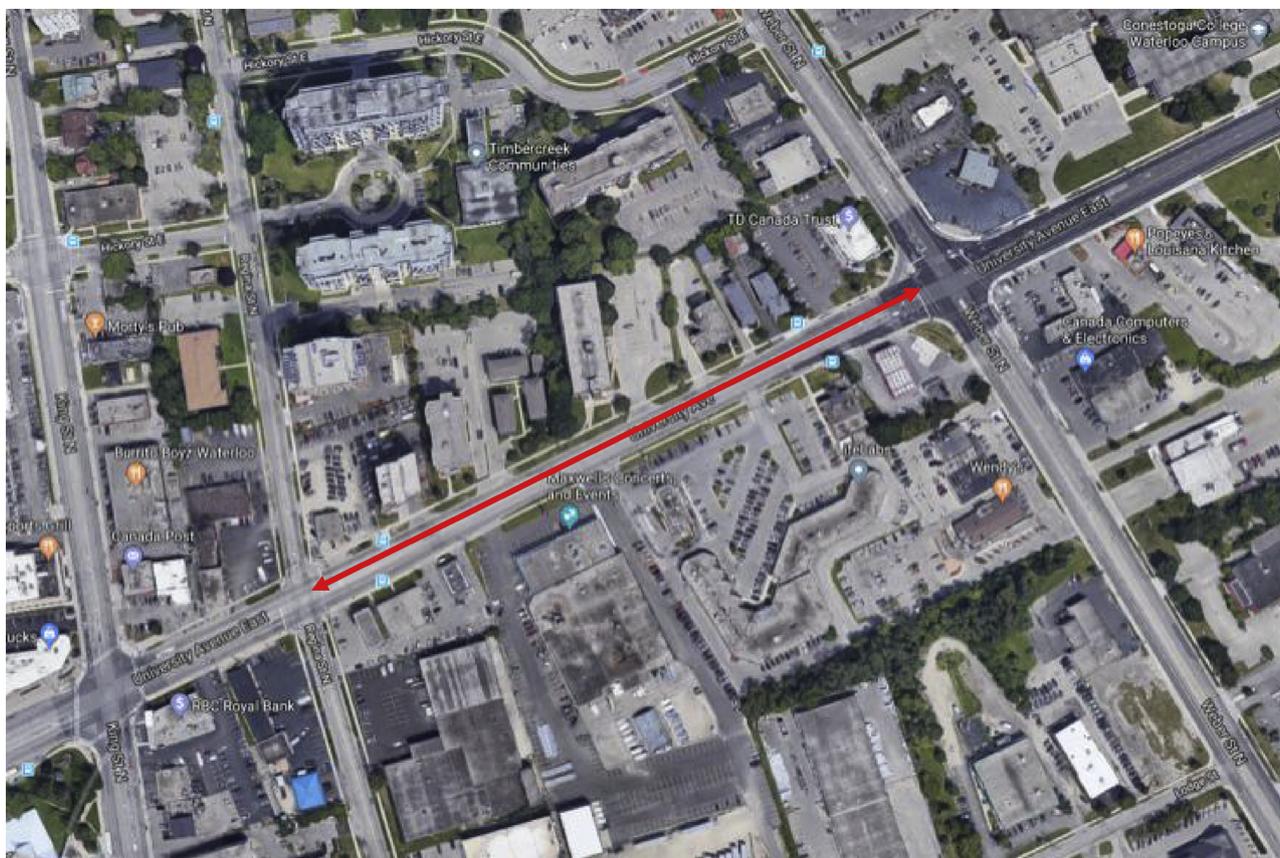
Fig. 8. Selected urban arterial to demonstrate model application (source: www.maps.google.com).

Desired Cycling Facility Pre-selection Nomograph (Fig. 10) is most applicable to two-lane, two-way roadways. However, it is still applicable to multi-lane situations. To apply the Nomograph to multi-lane facilities (e.g. 4LNB) the operating speed and the total combined traffic volume (i.e. AADT) travelling on the lanes directly adjacent to the cycling facility (e.g. shoulder lanes) should be considered. Since the study section is a 4-lane facility, assuming that AADT is equally distributed across the lanes in peak hours, the portion of AADT on the shoulder lanes is estimated as 50% of the total AADT (i.e. 11,188 vehicles per day). As presented in Fig. 10, the intersection of the section's adjusted AADT and design speed falls within the transition area from white to red, which indicates the need for separated bicycle lanes or cycling
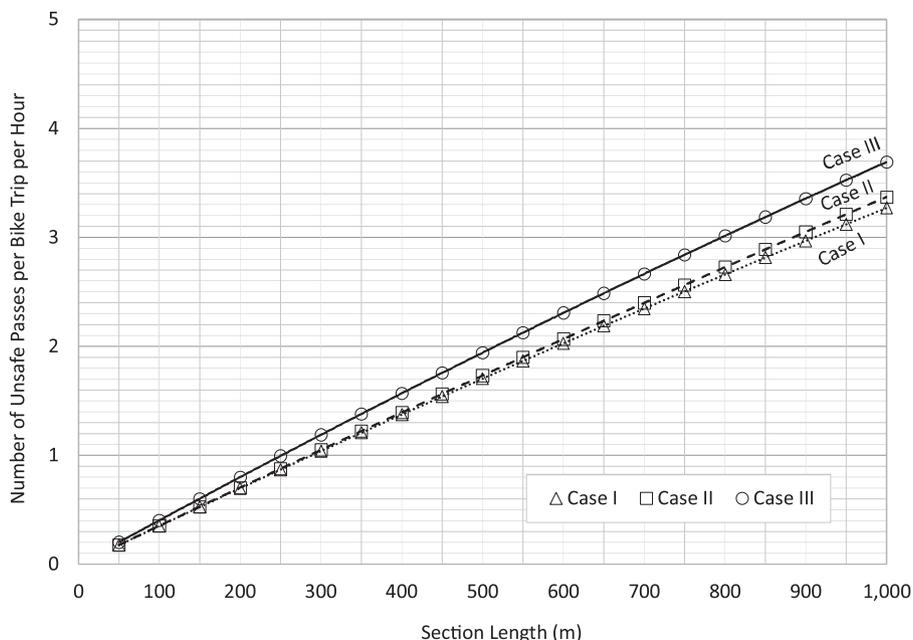

Fig. 9. The relationship between section length and the number of unsafe passing events per bicycle trip per hour for AADT = 22,375 vehicle per day considering signal timing cases.
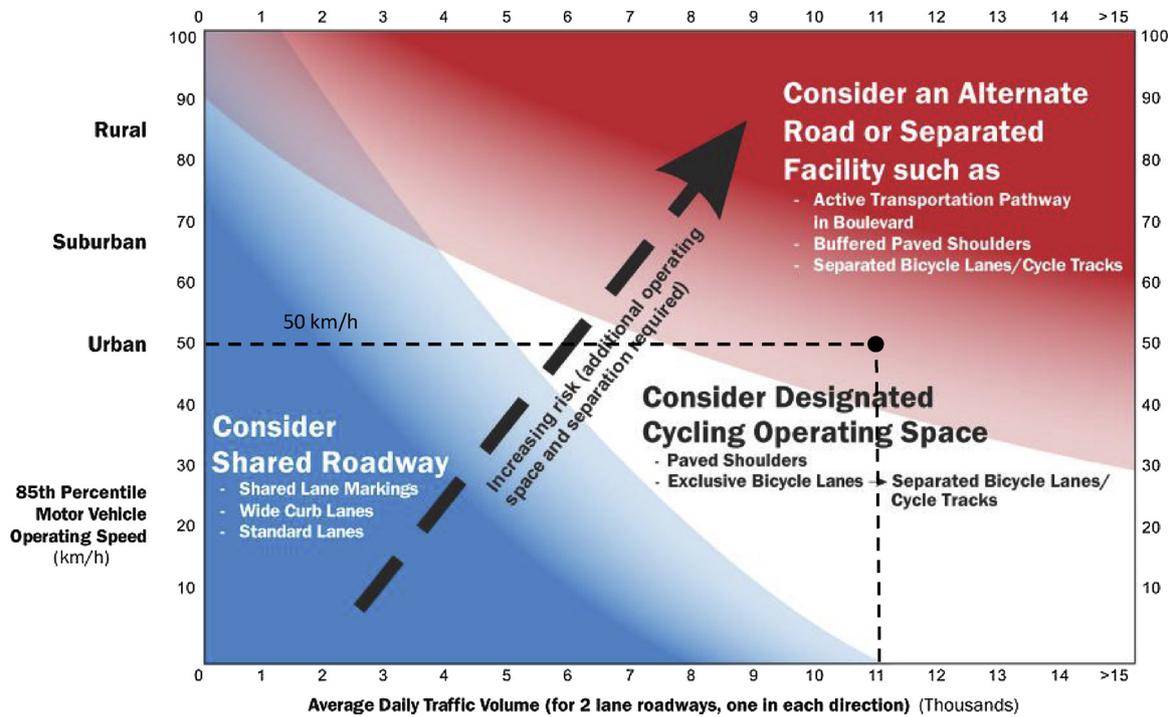
Fig. 10. Desired bicycle-facility pre-selection Nomograph (Ministry of Transportation Ontario, 2013).

tracks to accommodate cyclists along this section.

Oregon's Recommended Cycling Facility Separation Matrix (Fig. 11) is applicable to two-lane or multi-lane facilities based on the roadway's ADT (Average Daily Traffic) and posted speed limit. It is assumed that the study section's AADT and ADT are equal for the purpose of this analysis. As presented in Fig. 11, the section's ADT is greater than the maximum ADT considered in the matrix. Therefore, the intersection of the section's ADT (22,375 vehicles per day) and posted speed limit (31 mile per hour) falls in the gray area suggesting the need for fully separated cycling facilities such as buffered bicycle lanes, cycling tracks, or bicycle lanes. No additional information is provided in these guidelines regarding the rationale for such recommendations.

Furthermore, although it was shown earlier that the expected number of unsafe passing events are related to the section's length and traffic signal configurations, the recommendation by Ontario and Oregon guidelines are solely based on the section's design speed and AADT (or ADT) without considerations for section length or traffic signal timing. In addition, by comparing the diagrams in Figs. 9 and 10 some discrepancies are noted in the recommended cycling facilities for specific values of speed and AADT. For example, for design speed of 50 km/h 31 mph), Oregon guidelines permit the use of narrow lane facility-type up to ADT = 1500 vehicle per day. For ADT values greater than 1500 vehicle per day, provision of bike lane is recommended. Buffered bike lanes are recommended for complete separation between bicycles and
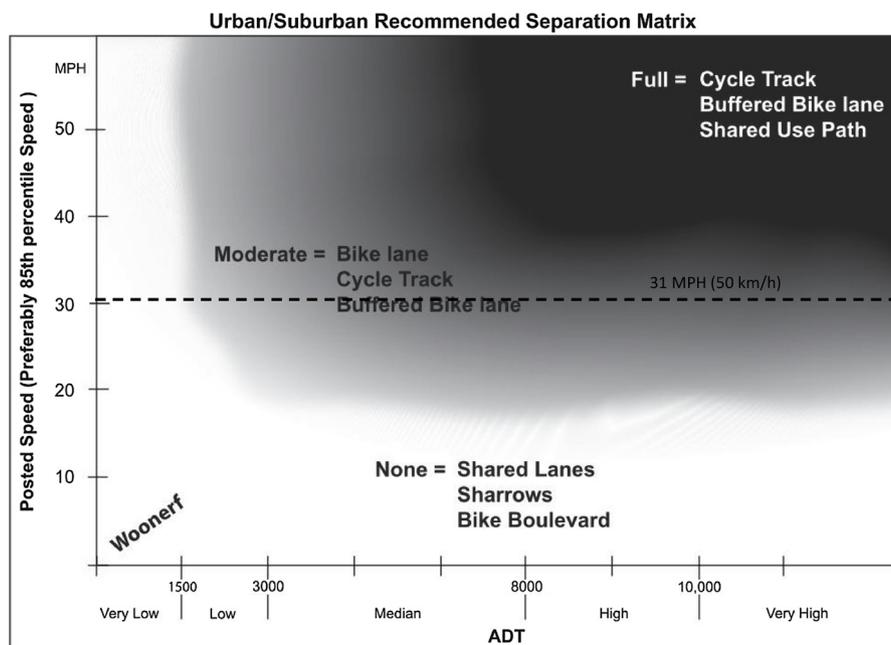

Fig. 11. Oregon urban/suburban recommended cycling facility separation matrix (Oregon Department of Transportation, 2011).

vehicles if ADT is greater than 6000 vehicle per day. In contrast, for the same design speed of 50 km/h, Ontario guidelines allow the use of narrow lanes for AADT values up to 5000 vehicle per day. Bicycle lanes are recommended if AADT is between 5000 and 8000 vehicle per day. The use of separate bicycle lanes are preferred if section AADT is greater than 8000 vehicle per day.

Inconsistencies between different bicycle facility design guidelines suggest the need for empirical foundations for developing these guidelines which was one of the objectives of this study. The proposed methodology can be used for quantitative comparison and prioritizing candidate road segments for implementation of dedicated cycling infrastructure.

5. Conclusions

In this study interactions between motorized vehicles and bicycles were studied by analyzing the overtaking behavior of motorized vehicles when passing bicycles on urban arterials. The concept of critical passing distance was introduced and based on that passing events were categorized into safe and unsafe. It was found that the probability of observing unsafe passing events on 4-lane urban arterials without on-street bicycle lanes is much higher when passing events are restricted. In restricted passing events, the passing vehicle is restricted from making lane changes or encroaching to adjacent lane due to the presence of other vehicles. It was shown that restricted passing is mainly determined by the formation and dispersion of vehicle platoons. Consequently, a methodology was developed to estimate the number of expected unsafe passing events on a given 4-lane urban arterial with no on-street bicycle lanes. The input parameters for the proposed methodology are bicycle demand, section length, AADT, speed limit, and upstream traffic signal configurations. The proposed method provides the basis for quantifying the risks imposed to cyclists while sharing the road with motorized vehicles. Thus, it can be used to prioritize urban arterial sections for provision of cycling facilities. The proposed method can also be used to evaluate the 'cycling safety level of service' on different road categories.

The critical passing distance in this study was assumed to be 1 m. There is no specific evidence to conclude that this is the appropriate value for differentiating between safe and unsafe passing manoeuvers. Furthermore, there is intuitive expectation that if such a differentiating value exists, that it should vary with the speed of vehicles on the roadway (i.e. greater passing distance is required at higher vehicle speeds). Nevertheless, in practice, the 1 m value appears to be in common use and in the absence of a value with a more rigorous justification, has been used within this paper. It should be noted that the approach described in this paper for finding the number of unsafe passing events could be applied using any other value for distinguishing between safe and unsafe passing events

The models presented in this paper are based on empirical distributions of passing distances collected in the Kitchener-Waterloo area in southern Ontario. Transferability of the models to other areas should be carefully evaluated based on local driving and cycling conditions. This is not limiting the application of the proposed methodology as similar empirical models can be developed based on field observations of passing distances in different areas. Yet, model coefficients and functional forms may differ from those presented in this research.

The models developed in this paper permit the estimation of the number of unsafe passing events per hour. These values are helpful when attempting to prioritize the allocation of resources for cycling infrastructure and specifically when attempting to decide on which

road segments' cycling infrastructure should be implemented first. However, it is not intuitively obvious how practitioners can use the output from the proposed models to justify when cycling infrastructure is warranted. Design guidelines or "warrants" (i.e. similar to traffic signal warrants) require not only the estimates provided by the proposed models, but also criteria or thresholds that determine the number of unsafe passing events per hour that is considered acceptable. Additional research is required to develop these criteria/thresholds across different road categories with different cycling facilities. This would enable guidelines that provide recommendations of a specific cycling facility (e.g. on-street bicycle lanes vs. separated bicycle paths) as function of expected number of unsafe passing events which can be estimated using the proposed methodology.

Potential conflicts between turning vehicles and through cyclists at intersection was not considered in this study. Additional research is required to quantify such conflicts as they are considered as a major safety concern for cyclists at intersections.

Finally, this paper has proposed linear models (Eqs. (5)–(7)) to estimate the probability of unsafe overtaking events as a function of AADT and section length. Additional investigation is warranted to determine if non-linear model structures would be more appropriate.

References

Chapman, J., 2011. Uniform vehicle code and state statutes governing bicycling, 2010: analysis of definitions and statutes. Trans. Res. Record 2247, 8–16.

Chuang, K.H., Hsu, C.C., Lai, C.H., Doong, J.L., Jeng, M.C., 2013. The use of a quasi-naturalistic riding method to investigate bicyclists' behaviors when motorists pass. Accid. Anal. Prev. 56, 32–41.

City of Toronto, 2003. City of Toronto Bicycle/Motor-Vehicle Collision Study. Retrieved from the website of the City of Toronto. Works and Emergency Services Department. https://www1.toronto.ca/city_of_toronto/transportation_services/cycling/files/pdf/car-bike_collision_report.pdf.

Grabow, M.L., Spak, S.N., Holloway, T., Stone Jr, B., Mednick, A.C., Patz, J.A., 2012. Air quality and exercise-related health benefits from reduced car travel in the mid-western United States. Environ. Health Perspect. 120 (1), 68.

Ipsos Reid, 2009. City of Toronto Cycling Study: Tracking Report (1999 and 2009). Retrieved from the website of the City of Toronto:. . http://www.toronto.ca/cycling/reports/pdf/cycling_study_1999_and_2009.pdf.

King, M., 2002. Bicycle facility selection: a comparison of approaches. Pedestrian and Bicycle Information Center, Highway Safety Research Center, University of North Carolina. Chapel Hill.

Legislative Assembly of Ontario, 2010. Bill 74: Highway Traffic Amendment Act (Safe Passing Bicycles). Retrieved from the website of the Legislative Assembly of Ontario:. http://www.ontla.on.ca/web/bills/bills_detail.do?locale=en&BillID=2364.

Mehta, K., Mehran, B., Hellinga, B., 2015. Evaluation of the passing behavior of motorized vehicles when overtaking bicycles on urban arterial roadways. Trans. Res. Record 2520, 8–17.

Ministry of Transportation Ontario, 2013. Ontario Traffic Manual Book 18 – Cycling Facilities. Retrieved from the website of the Ministry of Transportation Ontario:. http://www.raqsb.mto.gov.on.ca/techpubs/eps.nsf/0/825810eb3ddd203385257d4a0063d934/$FILE/Ontario%20Traffic%20Manual%20-%20Book%2018.pdf.

Minnesota Department of Transportation, 2007. Mn/DOT Bikeway Facility Design Manual. Retrieved from the website of the Minnesota Department of Transportation:. https://www.dot.state.mn.us/bike/pdfs/manual/manual.pdf.

Nosal, T., Miranda-Moreno, L.F., 2012. Cycle-Tracks, Bicycle Lanes, and On-street Cycling in Montreal, Canada: A Preliminary Comparison of the Cyclist Injury Risk. No. 12-2987. .

Oja, P., Titze, S., Bauman, A., de Geus, B., Krenn, P., Reger-Nash, B., Kohlberger, T., 2011. Health benefits of cycling: a systematic review. Scand. J. Med. Sci. Sports 21 (4), 496–509.

Oregon Department of Transportation, 2011. Oregon Bicycle and Pedestrian Design Guide. Retrieved from the website of the Oregon Department of Transportation:. 3rd edition. . http://www.oregon.gov/ODOT/Programs/TDD%20Documents/Bicycle-Pedestrian-Design-Guide.pdf.

Transportation Research Board, 2016. Highway capacity manual. A Guide for Multimodal Mobility Analysis, sixth edition. .