Cyclist Behaviour and Safety Towards Stop Signs. A Before-After Study on Stop-Controlled Intersections Using Video Trajectory and Surrogate Measures of Safety

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ABSTRACT

The installation of stop-signs in residential areas converting them from minor-approach-only stop (MAS) intersections to all-way-stops (AWS) intersections brings a positive perception by the general population. Although there is little research that has looked at the impact of AWS on cyclist behaviour and their safety effects. This paper aims at investigating the safety effect of converting MAS to AWS intersections using an observational before and after approach and surrogate measures of safety (SMoS). More specifically, the impact of AWS conversion is investigated using multiple indicators including cyclist speed measures, and the post-encroachment time of cyclist-pedestrian, cyclist-cyclist and cyclist-vehicle interactions. A multi-level linear models for site and approach variance, which was also used for the safety analysis, along with an ordered logit model where all the models were controlled for behavior variables, built environment features, approach and intersection geometry. The speed of the cyclist on the major approaches shows a slight decrease, while on the minor approach a systematic speed increase is seen for all the different speed statistics. Whereas there is a speed increase on the minor approaches, this does not translate into a decrease of PET or an increase of the proportion of very dangerous interactions.

Keywords: safety, all-way-stops, minor-approach-stop, surrogate measures of safety, post-encroachment time, cyclist speed

INTRODUCTION

Intersections represent the space on the road where the users from different traffic streams interact, making it the most important locations of the network from the safety and operations perspective. At intersections with a high number of users, signalized intersections are used t coordinate their movements efficiently and safely. At the other end, at intersections with very low, no signalization is deemed necessary, letting user follow the right-hand rule for the occasional interaction. In between, stop signs have proliferated and may be the most common traffic control device in urban areas. Canada, the USA, and some states and provinces have documentation describing their warrants for the installation of control devices. In Canada and Quebec, the Transport Association of Canada (TAC) and Quebec Ministry of Transportation (MTQ) respectively maintain the Manual on Uniform Traffic Control Devices for Canada (MUTCDC) (*1*) and the Tome V on Traffic Control Devices (*2*), which contain the warrants for the installation of control devices. The type of stop control device for an intersection is justified by the warrants, where motorized vehicular users are the main users considered. The warrants revolve around a) vehicle volume, b) vehicle speed, c) average delay for the minor road, d) safety concerns and e) visibility. In the Canadian warrants, cyclists are not considered in the users criteria, while the USA standards (*3*) consider cyclists and pedestrians for the volume criteria.

Over the past decade, urban cycling has been on the rise in North American cities such as New York City, Portland, San Francisco, Washington D.C., Montréal, Vancouver, etc. These cities have designed effective interventions to encourage cycling and improve cyclist comfort and safety to address this increase in bicycle demand (*4*, *5*). One reason for this growth is that cycling is often a more efficient commuting option in urban areas compared to other transport modes. Cyclists generally avoid congestion while benefitting from a healthy and inexpensive mode of transportation. In addition to the cyclist, society benefits from cycling through a reduction in emissions and noise pollution, cheaper infrastructure, and public health improvements (*6*). Cyclist safety at intersections remains a significant concern; at least half of the collisions between cyclists and drivers takes place at intersections (*7*, *8*). It has been shown that dangerous interactions and collisions between motor vehicles and non-motorized users increase with bicycle ridership (*9*, *10*). To better understand cyclist safety at intersections, several indicators have been developed to assess safety at approaches (*11*) and at the facility level (*7*, *12*). Cities have implemented cyclist-friendly treatments, such as cycling facilities, bike boxes, intersection geometric redesign, speed bumps and changes to the type of control at the intersection. The changes of the type of intersection control include the conversion of a minor-approach-only stop (MAS) intersection into an all-way-stop (AWS) controlled intersection and recently, the addition of bicycle traffic lights at signalized intersections.

The conversion of a minor-approach-only stop (MAS) intersection into an all-way-stop (AWS) intersection in principle are justified from the traffic operation and safety points of view. In general, warrants justify the installation of AWS signs when traffic, geometry, and/or road safety issues are identified, and some basic conditions are met. However, those conditions do not consider cyclists or consider them as a pedestrian or as a vehicle, which does not reflect how they behave towards the other users of the road.

Despite the existing body of knowledge, some significant controversies and limitations in the current literature can be highlighted regarding AWS intersections in the North American standards:

- The justification and use of stop signs have been debated in the literature. This controversy is related to the fact that stop signs have been used in many cases as a traffic calming measure to reduce vehicular speeds and traffic volumes going through residential areas. Although there is a positive perception by the general population of the installation of stop signs in residential areas (*13*), stop signs are explicitly forbidden to be used for traffic calming by manuals and guidelines.
- Despite the popularity of converting MAS to AWS intersections in urban areas, there is little research on the impacts of this countermeasure on cyclist safety and their behaviour. This is in part because of the lack of injury crash data before and after the installation of AWS.
- Finally, existing studies have focused on vehicles and pedestrian safety, with very few looking at cyclist safety.

To address the mentioned research gaps, this paper investigates the cyclist behaviour and their safety effects of converting MAS to AWS intersections using a before-after observational approach and surrogate measures of safety (SMoS), i.e. measures of safety that do not depend on the occurrence of crashes. For this purpose, a multi-level and ordered logit modelling approach is used to evaluate the impacts of the introduction of stop-signs on all approaches controlling for cyclist behaviour (using a helmet, making an avoidance maneuver or making a full stop), built environment, approach and intersection geometry. Among the SMoS, this research considers various cyclist speed measures and the post-encroachment time (PET) for cyclist-pedestrian, cyclist-cyclist and cyclist-vehicle interactions. This research is expected to provide some guidance for the revision of the existing warrants, considering the cyclist as a user of the intersection and their behavior towards stop signs.

BACKGROUND

Control Device Warrants

Stop sign guidelines between Canada and the USA are relatively similar, where the main difference is how the approaching speed is taken into consideration (see Table 1). Also, the American guidelines integrate bicyclist volumes as one of the possible requirements for the minor approach. In Canada, most of the provinces and territories follow the MUTCDC as their reference. Some Canadian provinces develop their own guidelines; several of them have fewer requirements than the MUTCDC. For instance, the AWS installation in Alberta does not have a vehicular crash rate criterion. In British Columbia, only the vehicular traffic volume and crash

Table 1 Canada and USA summary warrants for the AWS installation requirements

Country	Volume Criteria	Crash Rate	Speed Limits	Other comments (e.g., number of lanes, geometry, etc.)
Canada	V_1/V_2* ≈ 1 ▪ On the minor highway, 200 entering vehicles and pedestrians (combined) per hour over an 8hr period on an average day Average delay to the minor road of 30s during peak hour.	▪ 5 or more reported collisions, susceptible to correction by All-Way Stop-Signs, per year	▪ Safe vehicle speed on approach < 15km/h	▪ All-Way Stop -Signs can be installed as an interim to the installation of traffic signals; or ▪ As a transition phase to switch the stop control from a one road to an intersecting road
USA	V_1/V_2* ≈ 1 ▪ On the major road, at least 300 entering vehicles per hour over an 8hr period per average day; ▪ On the minor highway, at least 200 entering vehicles and pedestrians and cyclists (combined) per hour over the same 8hr period per day; Average delay to the minor road of 30s during peak hour.	▪ 5 or more reported collisions, susceptible to correction by All-Way Stop Signs, per year	▪ On the major road, if 85th percentile approach speed > 40mph (≈ 65 km/h) ▪ 70% of the minimum volumes listed under "Volume Criteria" should be taken	▪ All-Way Stop Signs can be installed as an interim to the installation of traffic signals; ▪ At locations with high pedestrian volumes ▪ Sight distance: road user cannot see intersecting street or negotiate intersection unless the conflicting highway also requires to stop

* The ratio of the traffic volume entering from the major highway to that of the minor highway

rates are considered for the implementation of AWS. Guidelines from Ontario and Quebec are mostly similar regarding motorized volumes, accident rates, etc. Whereas most of the requirements from Quebec and Ontario are based on the Canadian guidelines, the main difference is that the Federal guidelines do not have a requirement about the existence of other control devices within a specified distance. Ontario requires to avoid traffic lights or stop signs within 250 m in any direction, while for Quebec, the requirement is to avoid traffic lights on the major street within 250 m or stop signs within 150 m.

Cyclist behaviour and control devices at intersections

Various cyclist behaviors are linked to safety. Cyclist behaviour can include the choice of wearing a helmet, cycling speed, the use of a cellphone, compliance with traffic rules, etc. (*14*, *15*). There is a perception by some groups in society, that cyclist fail to obey road rules (*16*). A study in Sydney reported that cyclists believe that breaking the rules of traffic would translate into an increase in safety (*16*). Some studies focus on pedestrian or cyclist waiting time and dangerous crossing, mainly at signalized intersections (*17*). Collisions between pedestrians and cyclists are also a problem given the risk of injury for pedestrians (*18*). To encourage VRUs to follow the rules at intersections with high mixed flow, different measures have been taken, such as the use of traffic wardens in China (*19*).

At stop signs, cycling requires an additional physical effort to recover one's previous speed, while drivers simply have to shift their foot from the braking to the gas pedal (*20*). However, if a cyclist fails to come to do a complete stop, they balance slowing down or conduct a precautionary visual search (*21*). In a four stop-controlled intersections study in Kensington, California it was found that almost 90 % of cyclists slowed somewhat or came to a full stop at a two-way stop sign intersections, compared to 33 % of the cyclists at AWS (*21*). Traffic flow is improved when cyclist do not come to a complete stop at non-signalized intersection, since cars do not have to wait for the cyclist to clear the intersection (*20*). The State of Idaho in the USA implemented a law in 1982, allowing the cyclist to yield instead of coming to a complete stop at stop-controlled intersections, reducing bicyclist injuries (*22*).

Safety Analysis Methods at Intersections

Different methods are used to diagnose safety. Brüde and Larsson say that besides the average daily number of cyclist and vehicles, it may be hard to define the additional factors that have a significant influence on the number of crashes (*23*). However, Hunter found that, in addition to traffic volumes, the vehicle speed, the age of the bicyclist, and the presence of a right turn-lane could lead to a higher number of cyclist-vehicle collisions (7). Carter developed an index to evaluate safety at a macroscopic level for cyclists at intersections as a function of traffic volume, type of signalizations and geometric factors (11). Using accident records for studying cyclist safety has many downsides, such as under-reporting, a lack of accident data and information about the interaction process (*24*). Due to the lack of crash data, and other shortcomings of historical crash records, there has been an effort to find other methods, relying on surrogate measures of safety (SMoS), measures that do not require collisions to occur. To have a better understanding of the events, SMoS are often combined with other variables to provide a better understanding of safety and risk (*25*).

Computer vision techniques are becoming a useful tool for safety analysis due to the capacity to extract users' trajectories and classify them from videos (*26*). The microscopic data extracted from the videos have been used to identify patterns in traffic events (*27*). As an example, video analysis has been used to compare cyclist safety along with a set of different layouts of intersections with traffic lights (*28*) and develop conflict-based safety performance functions for signalized intersections (*29*). SMoS rely on severity indicators to measure the proximity of traffic events to a crash and/or the severity of the potential crash. Existing indicators can be classified into four leading families (*30*):

1. Time-to-Collision (TTC), defined as the time remaining until a collision of two road users assuming they continue travelling as initially planned;
2. Post-Encroachment-Time (PET), defined for users with observed crossing trajectories as the duration between the instant the first road user leaves the crossing zone and the

moment the second road user reaches the crossing zone;

3. Deceleration, which is the most common evasive action taken by a vehicle to avoid a collision (*30*); and
4. other indicators such as:
    a. speed, which is used as a predictor of collision occurrence and severity (*31*, *32*).

METHODOLOGY

For this study, the following steps were required:

a) Selection of sites: a sample of intersections was carefully selected to be treated
b) Data collection and video analysis.
c) Calculation of surrogate safety measures.
d) Statistical regression analysis.

Site Selection

An inventory of the intersections in Montréal was created for this research from the available geospatial data, the Montréal road network from the city and borough boundaries. The intersection points were defined based on intersecting polygon lines, then filtered automatically and reviewed manually to yield about 13,000 non-signalized intersections.

As a second step, a preliminary sample of 1,000 intersections was randomly selected from the population of intersections identified in the previous step. From this initial sample, a sub-sample of more than 100 of MAS intersections was chosen as candidates for treatment. The sub-sample was defined based on:

i) Stop-controlled intersections in local-local and local-collector streets
ii) Intersections where the cameras could be installed on existing infrastructure such as lamp posts
iii) Intersections with one or more approaches without stop signs (MAS intersection)
iv) The selected intersections are located in boroughs that agreed to participate in the study. Most of these boroughs had a previous request for the installation of stop signs, facilitating the implementation of the AWS intersections.

Finally, a second and final sub-sample of 31 sites was selected for the before-after study; these sites were chosen by the different boroughs as candidates for the study from the 100 sub-sample.

Traffic video data collection and processing

For video data collection, sites were instrumented using regular video action cameras installed in the proximity of the intersection, typically on a nearby lamp post. Sites were instrumented on weekdays for one day for the period before the treatment, and two days after it, between 9 am and 6 pm. The video cameras capture the movement of all road users inclusively within the zone of interest. Data were then processed to extract high-resolution road user trajectories at each site with the help of Lumina (*33*), a commercial software. This software automatically identifies, tracks and classifies each road user into one trajectory and labels them as pedestrians, bicycles, motor-vehicles (car, motorcycle, truck and bus) and unknown. As part of the data processing, a

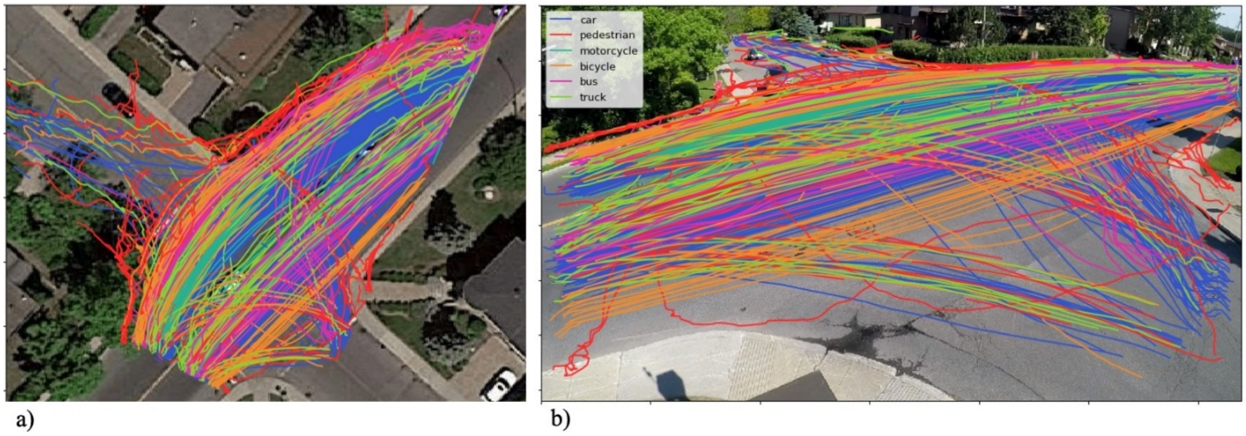


Figure 1. Example of processed video trajectories. a) represents the trajectories on a world space picture, while b) represents the trajectories on the image space.

calibration process is implemented where road user trajectories in the plane of the camera (*image space*) are projected onto the real world at ground level (*world space*). Once trajectory data is automatically generated, a manual review is carried out to correct VRU trajectories and to annotate the cyclist behaviour (use of helmet, avoid interaction, full stop) that will be used in this research; this process was accomplished using the tvaLib software (*34*), as part of the quality control. Figure 1 shows an example of a processed site where the user trajectories can be identified in different colours according to the represented road user.

Intersection Geometry and Stop Control Scenarios

A geometry inventory was generated for the study. This inventory includes intersection-level information such as intersection layout (number of approaches and branches) as well as approach-level information such as number of lanes per approach, presence of crosswalk, presence of stop-line, presence of bicycle facility, as well as the proximity to and type of control at the adjacent intersections. The list of variables used in this study are divided into intersection-level and approach-level characteristics, explained below:

Intersection-level features:

- ***Number of Branches***: intersections design varies greatly depending on the number of connecting streets, or branches or legs, which is typically three or four. A branch can be a unidirectional street serving as an approach or as an exit to the intersection, or it can be a bidirectional street serving as an approach and an exit to that intersection.
- ***Number of approaches****:* constitutes the portion of a branch dedicated to road users (motorized vehicles and VRUs) entering an intersection. There may be up to as many approaches as branches, but not more, and as few as two.
- ***Built environment:*** is represented by the population (density) or employment density, land use mix, or transit accessibility. A grid-based approach was defined for characterizing the land use around the intersection. The neighbourhood typologies

used for the intersections is a collection of data from Statistics Canada, then a grid based on a 500 m covering the entire island of Montreal was used (*35*).

- ***Non-Motorized Facilities***: includes the presence and the type of a cyclist facility at the intersection. The different kinds of bicycle facilities found in our dataset are shared road, painted bike-path, divided bike-path or no bike-path.

Approach level characteristics:

- ***Geometry***: number of lanes, presence and type of crosswalk marking (no crosswalk, stripped, two-lines and unique), presence of vehicles stop line, the width of the approach at the crosswalk level and 10 m upstream, presence and type of bicycle facility (bike-path).
- ***Type and Distance to the Previous Intersection****:* This is the distance to the upstream adjacent intersection (previous distance) and the kind of control on the upstream approach. The distance was measured from center to center of the intersections, and the type of intersection control is described as follow:
  - ***No-control:*** the upstream intersection is classified as MAS. It is assumed that the evaluated user is coming from a straight movement with no-control on the approach.
  - ***Stop –sign:*** the upstream intersection can be MAS or AWS, but the evaluated user comes from an approach with stop -sign.
  - ***Traffic light***: the upstream intersection is controlled by traffic lights. Hense, the evaluated user comes from an approach with traffic light
- **Cyclist movement:** variable indicating the direction of the user, it can be through, left turn or right turn movement.
- **Exposure:** binary variable indicating the presence of a VRU within a range of five seconds before and five seconds after the analyzed cyclist trajectory reaches its midpoint. This variable is to evaluate the effect of VRU presence on the cyclist' behaviour while navigating the intersection. At the same time, the five seconds threshold is considered as a limit where a cyclist can be influenced by the other road users.
- ***Stop -Control Scenarios:*** A set of four different conditions or scenarios were defined to evaluate the impact of traffic control after its implementation (Figure 2) as follows:
  - ***Scenario A****,* a major approach, with no stop sign before the conversion of a MAS intersection into an AWS intersection
  - ***Scenario B****,* a major approach, with a stop sign after the conversion of a MAS intersection into an AWS intersection
  - ***Scenario C****,* a minor approach, with a stop sign before the conversion of a MAS intersection into an AWS intersection

- ***Scenario D***, a minor approach, with a stop sign after the conversion of a MAS intersection into an AWS intersection

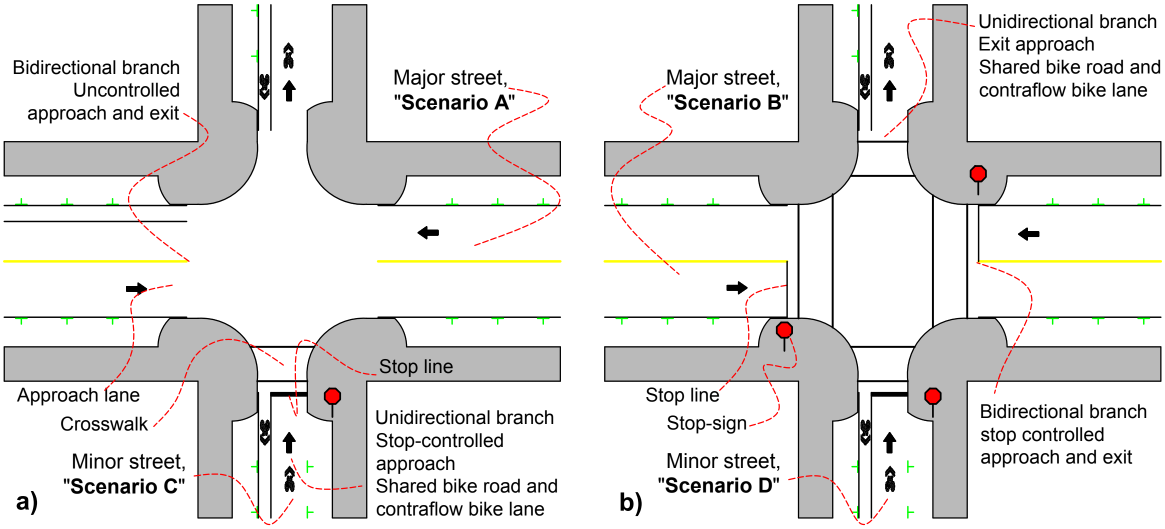


Figure 2 Example of the four scenarios on an intersection with four branches and three approaches in a before (a) and after (b) treatment. a) represents an intersection where the minor street is stop -sign controlled and b) it is an all-way stop -sign intersections

Safety Indicators

The safety analysis performed in this study makes use of the following safety indicators that are part of the surrogate safety approach:

- ***Road users speed***: There are strong correlations between speed, crash likelihood, and severity, as shown in several studies (*36–39*). For this work, different speed statistics are generated in an automated way extracted from the various user trajectories (all positions and speeds) of the video analysis: the minimum calculated as the 15th percentile ($v_{15^{th}}$), median (v_{med}), and maximum calculated as the 85th percentile ($v_{85^{th}}$) speed.
- ***Post-Encroachment Time (PET)***: It measures a situation defined as "near misses", where a collision is avoided by a small margin. The PET is calculated as the time difference where the first road-user (user "a") leaves the path or crossing zone before the second road-user reaches the mentioned zone (user "b"), as represented in Figure 3 (*30*).
- **PET categories:** PET values are characterized in terms of severity according to their values, with the thresholds used by Zangenehpour et al. (*40*), where the PET interactions are divided four categories:
  - Very dangerous, PET ≤ 1.5 s
  - Dangerous, 1.5 s < PET ≤ 3 s
  - Mild interaction, 3 s < PET ≤ 5 s
  - Safe interaction, PET > 5 s

In addition to safety indicators, three cyclist variables about their behavior were manually observed: the use of a helmet, an avoidance maneuver by the cyclist during the interaction or the cyclist coming to a full stop).

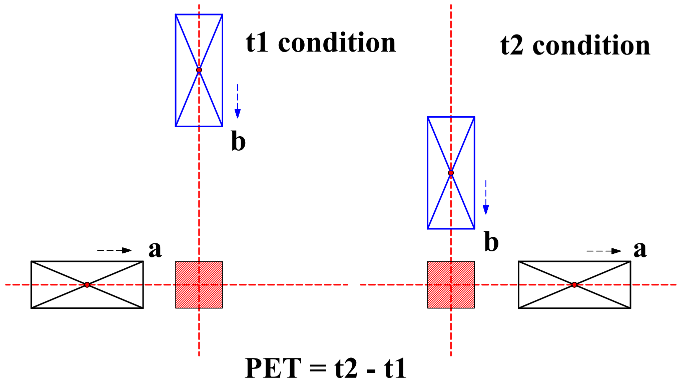


Figure 3. Post-Encroachment Time (PET) description

RESULTS

Data Summary

After the video was automatically processed, the first four hours for one day before and one day after the stop signs installation in all the approaches (from 8 am to 12 pm) have the VRU trajectories manually verified and corrected, providing a ground truth sample of peak and off-peak hours of each day. An inventory of the processed video data is presented in Table 2, with general information such as the number and type of intersection, approaches (stop-controlled or

Table 2 Data inventory

	Description	Counts			Percent (%)		
		Before	After	Total	Before	After	Total
Traffic Data	Major approach	**29,214**	**23,846**	**53,060**	55.1	44.9	**76.9**
	Pedestrians	3,186	3,085	6,271	50.8	49.2	11.8
	Cyclist	2,914	1,033	3,947	73.8	26.2	7.4
	Motorized	23,144	19,728	42,872	54.0	46.0	80.8
	Minor approach	**8,454**	**7,459**	**15,913**	53.1	46.9	**23.1**
	Pedestrians	1,153	1,273	2,426	47.5	52.5	15.3
	Cyclist	994	379	1,373	72.4	27.6	8.6
	Motorized	6,307	5,807	12,114	52.1	47.9	76.1
	Total number of users	**37,668**	**31,305**	**68,973**	**-**	**-**	**100.0**
General Information (number of)	Distinct intersections		30			-	
	Three branches		10			-	
	Four branches		21			-	
	Video data (h)	121	124	245	49	51	100
	Total approaches	101	101	202	50	50	100
	Stop-controlled approaches	59	101	160	58.4	-	73.2
	Uncontrolled approaches	42	0	44	41.6	-	26.8

not), hours of analyzed video and traffic data in terms of the number of road users crossing the intersection and their types. Following, Table 3 includes a statistical summary of cyclist speed and PET of interactions where the 5th centile (Q-05), mean, median, 95th centile (Q-95) and Standard Deviation (S.D.) are obtained for each of the three speed variables and PET from the video trajectories for each scenario.

Cyclist Speed Analysis

An initial observational analysis of cyclist speed for the major and minor approaches is performed from Figure 4 and Figure 5. For the major approach it can be remarked from Figure 4 that the cyclist speeds show little change, but it is significant according to the Kolmogorov-Smirnov (K.S.) test. Except for Q-05, all statistics for all the computed speeds decrease going from MAS to AWS, including the standard deviations (S.D.) with reductions from 8.76 % to 21.1 %.

The minor approach presents a systematic speed increase slightly in all the different evaluated indicators, where all the changes are significant according to the K.S. test. This is expected, since the minor approaches already had a stop sign before and, once the intersection becomes AWS, cyclists have the confidence that the vehicles on the major approach will stop and yield. Despite the speed increase, the S.D. has a small decrease in all the speed values, showing a more uniform cyclist speed behaviour.

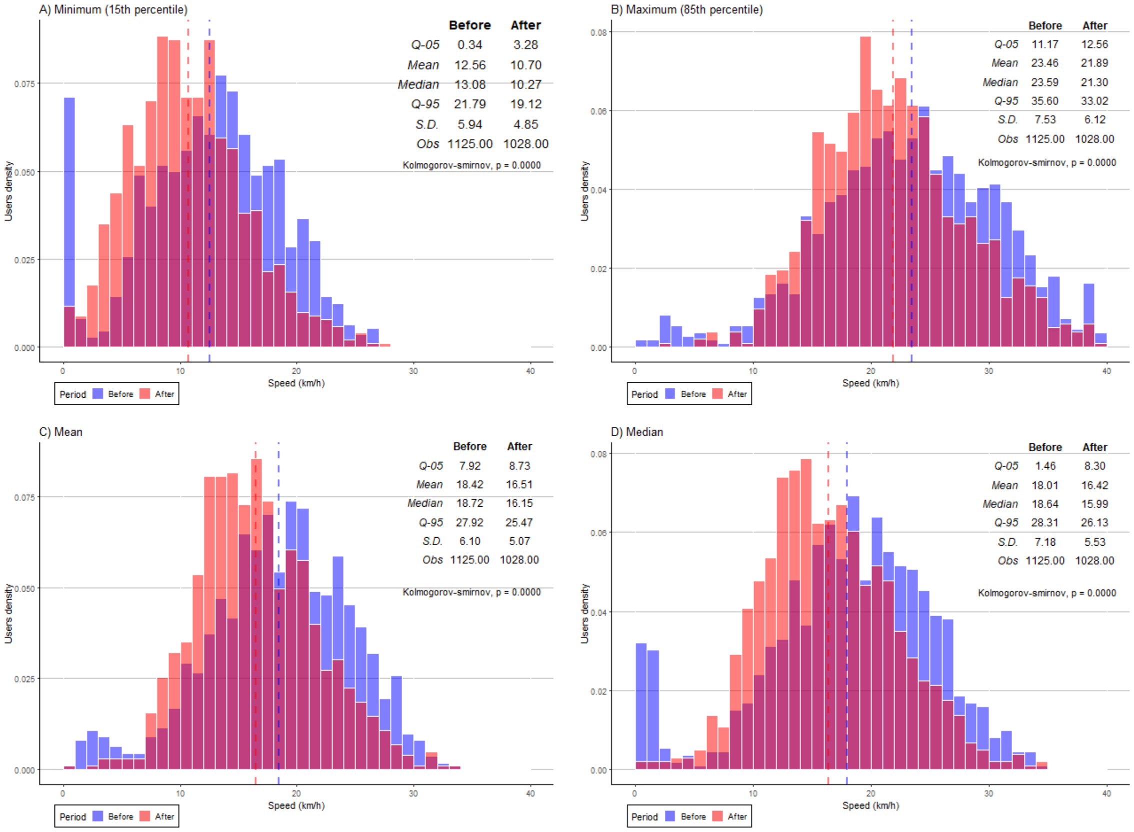
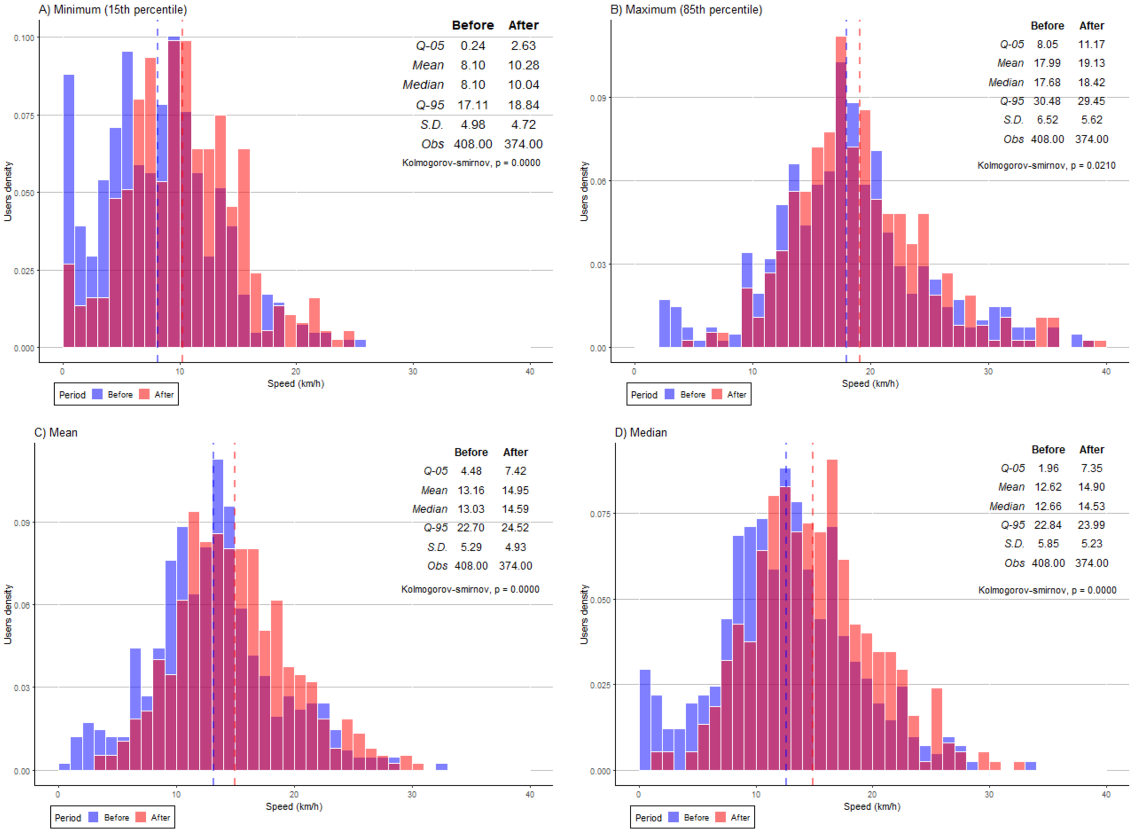


Figure 4. Cyclist speed histogram distribution for the Major approaches for: A) Minimum (15th percentile), B) Median, and C) Maximum (85th percentile) speeds observations for the before and after period for all the locations

Table 3 Cyclist speed and PET summary statistics per scenario

Scenario	Variable	Speed variables					Observations
		Min (Q-05)	Mean	Median	Max (Q-95)	S.D.	
A	Minimum Speed	0.33	12.66	13.15	21.79	5.92	1,043
	Median Speed	1.43	17.94	18.60	28.25	7.18	
	Maximum Speed	11.26	23.11	23.18	34.59	7.31	
	PET	1.54	4.42	4.73	7.18	2.04	36
B	Minimum Speed	3.66	10.85	10.38	19.34	4.81	971
	Median Speed	8.40	16.49	16.04	26.16	5.51	
	Maximum Speed	12.52	21.71	21.15	32.55	6.03	
	PET	0.87	3.98	3.69	8.00	2.45	64
C	Minimum Speed	0.36	8.20	8.15	17.23	4.98	376
	Median Speed	2.01	12.73	12.67	22.86	5.87	
	Maximum Speed	8.15	18.04	17.58	30.64	6.50	
	PET	0.00	3.60	3.20	6.80	2.23	49
D	Minimum Speed	3.20	10.28	9.98	18.79	4.61	364
	Median Speed	7.60	14.89	14.50	23.54	5.07	
	Maximum Speed	11.50	19.07	18.41	28.67	5.48	
	PET	0.79	4.34	4.08	8.38	2.62	76



A) Minimum (15th percentile)

	Before	After
Q-05	0.24	2.63
Mean	8.10	10.28
Median	8.10	10.04
Q-95	17.11	18.84
S.D.	4.98	4.72
Obs	408.00	374.00

Kolmogorov-smirnov, p = 0.0000

B) Maximum (85th percentile)

	Before	After
Q-05	8.05	11.17
Mean	17.99	19.13
Median	17.68	18.42
Q-95	30.48	29.45
S.D.	6.52	5.62
Obs	408.00	374.00

Kolmogorov-smirnov, p = 0.0210

C) Mean

	Before	After
Q-05	4.48	7.42
Mean	13.16	14.95
Median	13.03	14.59
Q-95	22.70	24.52
S.D.	5.29	4.93
Obs	408.00	374.00

Kolmogorov-smirnov, p = 0.0000

D) Median

	Before	After
Q-05	1.96	7.35
Mean	12.62	14.90
Median	12.66	14.53
Q-95	22.84	23.99
S.D.	5.85	5.23
Obs	408.00	374.00

Kolmogorov-smirnov, p = 0.0000

Figure 5 Cyclist speed histogram distribution for the Minor approaches for: A) Minimum (15th percentile), B) Median, and C) Maximum (85th percentile) speeds observations for the before and after period for all the locations

Regression Analysis

The 20 covariates presented in the methodology (section 3.3) were evaluated using a multi-level regression model (random effect regression model), with a 95 % confidence interval, where the site and approach I.D. were included as random effects given the hierarchical nature of the data. Some variables were removed from the model due to their high correlation. i.e., the number of stop signs and period of analysis were removed due to their correlation with the scenario variable, and the number of lanes for the correlation with the crosswalk width. Other variables, like the employment density, land use mix and public transit accessibility, were removed after an initial evaluation due to their non-significant effect in the model. Also, the random effect that corresponded to the I.D. number of the intersection was removed from the speed analysis due to their virtually null effect in the different models. In contrast, the random effect of the different approaches was kept.

Cyclist Speed

The effects of treatment on speed indicators were introduced through the scenarios defined above, and the main results are as follows (see **Table 4**):

- Scenario A is the major approach without a stop sign in the before period, considered as the base scenario in the regression model.
- Scenario B represents the treatment or installation of a stop sign at the major approach in the after period. Based on its regression coefficient, the speed reduction is of 0.96 km/h for the predicted mean $v_{15^{th}}$ after controlling for other variables. This represents a speed reduction of nearly 7 % with respect to the base scenario.
- Scenario C represents the minor approach before AWS treatment implementation. In this scenario, the speed difference is of 4.15 km/h for the predicted mean $v_{15^{th}}$ (30 % lower speed compared to the base scenario) after controlling for other factors. As suspected, this suggests that approaching cyclist speeds already had lower speeds due the stop sign and that vehicles in the major approach have the priority.
- Scenario D represents the minor approach after treatment implementation. For this scenario, a speed increase of 2.96 km/h is observed for the mean $v_{15^{th}}$ compared to Scenario C. This speed represents nearly a 10 % of speed reduction compared to the base scenario or slightly more than 20 % speed increase than Scenario C.

The ANOVA tests show a significant difference for most of the scenario comparisons. The comparisons that do not show any difference are the one between the major and the minor approach in the AWS condition for the three speed statistics and the comparison between the MAS and AWS condition of the $v_{85^{th}}$ for the minor approach before and after, which indicates that the cyclist maximum speed is not affected by adding stop signs at other approaches.

The approach-level factors have mixed significant results according the speed variable that is evaluated, $v_{85^{th}}$ being the one with the most significant variables and the $v_{15^{th}}$ the one with the smallest number of significant variables. For the median speed, increasing the approach width will reduce the cyclist speed, also the turning movements reduce the speed, as expected, but the right turn has a bigger speed decrease. For the site-specific variables, only the population density is significant, decreasing the median and maximum cyclist speed.

Additionally, to the variable analysis, the S.D. for the site and approach I.D. have a variability between 1.53 and 2.28 km/h for the different predicted speeds variables. The previous shows a

Table 4 Model results for cyclist speed analysis

	Coefficients	**Minimum**		**Median**		**Maximum**	
		Estimates	P-value	Statistic	P-value	Estimates	P-value
Treatment	(Intercept)	13.61	**0.001**	20.92	**0.001**	28.57	**0.001**
	Scenario B	-0.96	0.093	-1.10	0.098	-2.40	**0.001**
	Scenario C	-4.15	**0.001**	-4.36	**0.001**	-3.90	**0.001**
	Scenario D	-1.19	0.162	-1.70	0.088	-3.23	**0.002**
Approach	Crosswalk presence	0.65	0.116	0.48	0.321	-0.62	0.232
	Stop-line presence	-1.24	**0.022**	-0.27	0.669	1.92	**0.004**
	Approach width	-0.08	0.067	-0.11	**0.030**	-0.15	**0.003**
	Bike-path	-0.46	0.391	0.02	0.972	0.03	0.962
	Right Turn Movement	-1.05	**0.001**	-1.92	**0.001**	-2.55	**0.001**
	Left Turn Movement	-0.33	0.379	-1.11	**0.011**	-1.29	**0.006**
Site	Previous distance	0.01	0.855	0.01	0.852	0.01	0.917
	Previous no stop-control	3.52	0.131	1.67	0.535	-1.77	0.516
	Previous stop-sign	2.12	0.345	1.1	0.674	-1.27	0.632
	Previous traffic light	2.62	0.259	1.95	0.470	-0.92	0.737
	Four branches	0.49	0.603	0.97	0.414	1.87	0.151
	Population density	-0.03	0.054	-0.04	**0.022**	-0.05	**0.021**
Model analysis	Random Effect (Std Dev)						
	Site ID	1.529		2.011		2.281	
	Approach ID	1.777		2.074		1.918	
	Residual	4.587		5.295		5.74	
	Pseudo-R2 Marginal	0.131		0.128		0.1194	
	Pseudo-R2 Conditional	0.311		0.328		0.3064	
	Site groups numbers	30		30		30	
	Approaches groups numbers	101		101		101	
	Observations	2,754		2,754		2,754	
	AIC	16,401		17,193		17,623	
Scenario analysis	Anova test (p-value), effect scenarios comparison						
	Major approach with vs without stops	**0.001**		**0.001**		**0.001**	
	Minor approach before vs after	**0.001**		**0.001**		0.278	
	Major vs minor approach (before)	**0.001**		**0.001**		**0.001**	
	Major vs minor approach (after)	0.736		0.454		0.303	
	Approach without vs with stops	**0.001**		**0.001**		**0.001**	

variability between 8 and 12 % of the predicted cyclist speed values for the different sites and approaches.

PET Analysis

As a first step, the PET cumulative distributions are analyzed for the different scenarios (Figure 6). Interactions are divided into three categories: cyclist-pedestrian interactions (CPI), cyclist-cyclist interactions (CCI) and cyclist-vehicle interactions (CVI). When the PET is not controlled for additional factors but the treatment, as in Figure 6, its effect is variable for the different users and approach type. While there are some clear shifts in the distribution with decreases of the

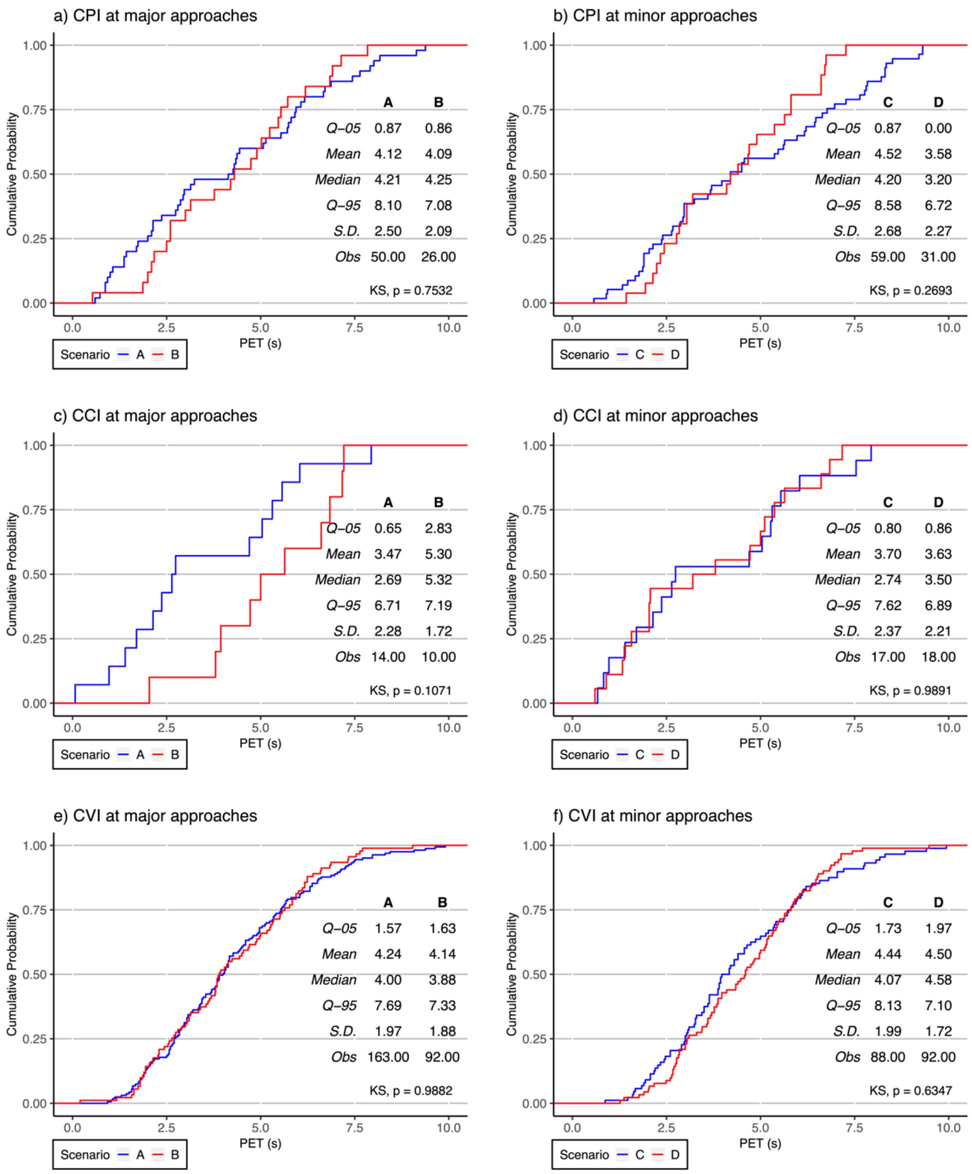


Figure 6. PET cumulative distribution functions. a) Cyclist - Pedestrians at major approaches, b) Cyclist - Pedestrians at minor approaches, c) Cyclist - Cyclist at major approaches, d) Cyclist - Cyclist at minor approaches, e) Cyclist - Vehicles at major approaches, f) Cyclist - Vehicles at minor approaches

Table 5 PET model results between cyclist and other users

	Coefficients	Multi-linear		Order logit	
		Estimates	P-value	Log (odds)	P-value
Treatment	Intercept	2.33	0.074	-	-
	PET dangerous	-	-	1.09	0.299
	PET mild	-	-	-0.75	0.473
	PET safe	-	-	-2.03	0.054
	Scenario B	-0.23	0.484	-0.15	0.602
	Scenario C	0.23	0.705	0.26	0.619
	Scenario D	0.20	0.741	0.01	0.978
Behaviour	Conflicts Cyclists	-0.52	0.289	-0.45	0.334
	Conflicts Vehicles	0.03	0.920	0.30	0.295
	Median Speed	0.06	**0.004**	0.07	**0.001**
	Right Turn Movement	0.05	0.897	0.13	0.696
	Left Turn Movement	0.01	0.991	-0.04	0.903
	Helmet	-0.50	0.089	-0.38	0.167
	Avoid	-1.30	0.085	-1.55	**0.020**
	Full stop	1.10	0.217	1.44	0.066
Approach	Crosswalk presence	0.30	0.791	-0.13	0.887
	Bike-path	0.34	0.186	0.33	0.154
	Approach width	0.01	0.774	-0.01	0.608
Site	Previous distance	0.01	0.999	0.01	0.879
	Four branches	0.54	0.254	0.45	0.209
	Population density	0.01	0.943	-0.01	0.561
Model analysis	Site ID	0.256		-	
	Approach ID	0.001		-	
	Residual	2.050		-	
	Pseudo-R2 Marginal	0.063		-	
	Pseudo-R2 Conditional	0.077		-	
	LR chi2	-		31.950	
	Pr(chi2)	-		0.015	
	R2	-		0.096	
	AIC	1,518		902	
	Observations	341			
Frequency	PET very dangerous	-		34 (10.0 %)	
	PET dangerous	-		96 (28.2 %)	
	PET mild	-		99 (29.0%)	
	PET safe	-		112 (32.8 %)	
Scenario analysis	Anova test (p-value), scenarios comparison				
	A vs B	0.0665		-	
	C vs D	0.9287		-	
	A vs C	0.1938		-	
	B vs D	0.4549		-	
	A vs (B+C+D)	0.1336		-	

proportion of low PETs for CPIs at minor and major approaches and for CCI at major approaches, the K.S. tests indicate no significant differences for the different interaction categories.

Two models, a multi-linear model and an ordered logit model for the PET categories, were estimated (**Table 5**), but both show very poor fit, with few significant variables. Cyclist median speed is the one variable significant in both models, surprisingly associated with higher PET in the multi-linear model higher probabilities of a safer category of PET in the ordered logit model. Intuitively, higher speeds would be associated with smaller time margins, but may be associated with other, safe, cyclist behaviours. The other significant variable is the binary variable for an avoidance maneuver by the cyclist, associated with a higher probability of a dangerous interaction. The causal link probably goes the other way around: cyclists involved in dangerous (low PET) interactions will perform an avoidance maneuver to avoid a crash. Finally, none of the scenario comparisons with the ANOVA tests for the multi-level model where significant. It seems that the PETs of cyclist interactions does not change with the conversion to AWS. Although their speed is affected, this does not translate into any change in their management of time margins with other road users. This does not mean that their safety is not changed, as speed has changed in different directions on the major and minor approaches, bringing potential changes in terms of crash severity, and other aspects of safety, measured by other indicators like TTC, may have been affected. Though not significant, the PET value of CCIs is half a second lower than with a pedestrian or with a vehicle. It should be noted that the mean PET value of a cyclist with a pedestrian and a vehicle are similar (2.30 s) indicating the compliance of cyclist towards pedestrians.

CONCLUSIONS

In this research, the behaviour of cyclists and the safety effect of stop signs is investigated using a before and after study on intersections that were transformed from minor-approach-only stop (MAS) into an all-way-stop (AWS). The cyclist speed behaviour was evaluated with a multi-level linear models for site and approach variance, which was also used for the safety analysis, along with an ordered logit model where all the models were controlled for behavior variables, built environment features, approach and intersection geometry.

The speed of the cyclist on the major approaches shows a slight decrease, while on the minor approach a systematic speed increase is seen for all the different speed statistics. Despite the contrary speed results on the different approaches, cyclist in the AWS intersections are showing similar speed values (around 10.0 km/h). Whereas the minor approaches show a speed increase, this is not translated to a decrease of PET or an increase of proportion of very dangerous interactions. Though not significant, the PET value of CCIs is half a second lower than with a pedestrian or with a vehicle. It should be noted that the mean PET value of a cyclist with a pedestrian and a vehicle are similar (2.30 s) indicating the compliance of cyclist towards pedestrians.

Future work will deal with other indicators of cyclist behavior and safety to better understand the effect of stop signs. Despite their popularity, stop signs may in fact play very little role in the safety of some road users like cyclists. While this study shows little effect at individual sites, it remains to be seen whether there is a network or systemic effect of the generalized use of stop signs for traffic calming in residential neighbourhood.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Bismarck Ledezma-Navarro, Luis Miranda-Moreno, Nicolas Saunier; data collection: Bismarck Ledezma-Navarro; analysis and interpretation of results: Bismarck Ledezma-Navarro; draft manuscript preparation: Bismarck Ledezma-Navarro and Nicolas Saunier. All authors reviewed the results and approved the final version of the manuscript

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