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Are bicycle lanes effective? The relationship between passing distance and road characteristics

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ABSTRACT

An on-road observational study of 162 cyclists was conducted in the Australian cities of Melbourne, Perth, Geelong, and Bendigo. Participants had a distance sensor and two video cameras fitted to their bicycle for two weeks while they cycled on their usual routes, producing 46,769 events where a motor vehicle passed a bicycle. This was the largest study to-date to record passing behavior on public roads, and a large number of road and traffic attributes that might affect passing distance were included in the analysis.

When drivers pass cyclists on roads with painted bicycle lanes, they tend to give more space than on roads without bicycle lanes. This is true even when controlling for the space available on the roadway. Drivers also travel in a more predictable fashion, with less variability in passing distances when a bicycle lane is present. Protected bicycle lanes completely remove the risk of passing events less than 1 m. However, where it is not possible to build a protected bicycle lane it is preferable to have a painted bicycle lane than no bicycle lane at all.

Other protective factors include: wider lanes, single lane roads, smaller vehicles, and the removal of on-street parking.

1. Introduction

Multiple studies have attempted to quantify the distance given by passing vehicles to bicycles on public roadways. Close passing is studied because of the unpleasant feeling cyclists report when close passed, and because it may relate to collisions on the road.

As discussed by Walker et al. (2014), close passes can be hypothesized to occur on a spectrum between collisions and near misses, such that frequent near misses will function as a proxy for infrequent collisions. There is also some suggestive evidence that close passing events are a predictor of actual collisions (Dozza, 2019; Lu et al., 2011). It follows that even a small shift in the passing distance distribution towards a greater passing distance could be considered to suggest a reduced risk of collisions.

Close passing also relates to a cyclist's perception of safety on the road (Aldred, 2016; Balanovic et al., 2016). Given the health benefits of cycling shown by Celis-Morales et al. (2017) and others, a road network that experiences a high rate of close passes may discourage cycling, with significant negative public health consequences.

Researchers have attempted to predict which factors make close passes more likely, in the hope that it may aid policy makers and the broader public in their efforts to make cycling safer.

Rubie et al. (2020) performed a systematic literature review and meta-analysis of the current literature on passing distance. They make the following findings which we confirm in this paper:

1. Vehicles pass closer on narrow roads.
2. Larger vehicles, in particular buses and trucks, pass closer than smaller vehicles.
3. Faster vehicles pass wider than slower vehicles, but not enough to compensate for the extra force exerted by vehicles passing at higher speeds.
4. Vehicles pass closer on busier roads.

They also make the following findings which, with new evidence, we contest:

1. Vehicles pass closer on single-lane roads.
2. Mixed results for on-street parking.
3. Mixed results for bicycle lanes, with meta-analysis pointing to no significant effect for painted lanes.

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Previous observational studies in this area (summarized in Table 1) often reach contradictory results. Much of the confusion in the results is due to differences in how data was collected and analyzed. Predicting what factors make close passes more likely has proven a difficult endeavor. There are five problems with previous literature that this study aims overcome:

1. Many studies have only collected data using a few cyclists or on a select number of roads.
2. Road related variables, such as roadway widths, are often either not recorded or recorded sporadically.
3. Many studies have relied upon ultrasonic sensors, which are cost effective, but difficult to utilize accurately. If the sampling rate of ultrasonic sensors is not high enough, vehicles traveling at high speeds may not be detected or there will not be sufficient samples to robustly determine passing distance. If wing mirrors are not accounted for in data processing, the exact height of the sensor from the ground has a large impact on the likelihood that a wing mirror will be detected. If wing mirrors are detected in some samples but not others, this will result in an inconsistent measure of passing distance between vehicles.
4. Not all studies use a rear camera to record passing events. If a rear camera is not used, it is impossible to know whether the vehicle overtaking was in an adjacent lane to the bicycle before the overtaking event began. If such events are counted as passing events, the rate of close passing on multi-lane roads could be skewed significantly.
5. There is disagreement about the most appropriate statistical methods to analyse passing distance.

Nowhere are these difficulties more apparent than in the literature surrounding whether painted bicycle lanes change passing distance. For example, Parkin and Meyers (2010) and Mackenzie et al. (2019) both found that vehicles passed closer in the presence of a bicycle lane. In contrast, Love et al. (2012), Chuang et al. (2013), and Bella and Silvestri (2017) found that passing distances increased in the presence of a bicycle lane. Van Houten and Seiderman (2005) also found that cars drive closer to the center of the road when a bicycle lane is present. But as Table 1 shows, most of these studies were conducted with a small number of cyclists or on a small number of roads. As there are many unmeasured factors on any particular roadway that might affect passing distance, it is difficult to be sure that any one road had closer passing distances due to the presence or absence of a bicycle lane, and not some other factor.

The largest study of passing distance prior to that presented here, Beck et al. (2019), aimed to overcome many of these issues. They recruited 60 cyclists on a variety of roads in Melbourne, Australia. Yet Beck et al. (2019)'s methodology failed to control for roadway width, bicycle lane type, or roadway type, which were found to be important factors in the analysis presented here. In addition, Beck et al. (2019) had the limitations described above regarding no rear camera footage, low sampling rates, and no explicit treatment of wing mirrors.

Beck et al. (2019) came to the counter-intuitive conclusion that even roads with footpath-adjacent bicycle lanes have lower average passing distances than roads with no bike lane at all. The paper presented here disputes Beck et al. (2019)'s findings, suggesting their conclusion was the result of flawed methodology and should be discounted.

The study presented in this paper is the largest to date that measures the predictors of passing distance given to bicycles by passing vehicles. In contrast to previous studies, this study used more carefully calibrated ultrasonic sensors sampling at higher rates. Noise reduction techniques were also used to ensure a consistent measurement of passing distance. Our large sample size enables us to average out random factors that might affect passing distance for any one cyclist, or on any one road. Further, more detailed information was collected about road related variables that might affect passing distances than in all previous studies.

A further point of contention in the literature is the methodology used to analyze passing distance data. The simplest way to understand what factors affect vehicle passing is to measure the average passing distance using a linear regression. However, the use of this method implies that a 1 cm difference in passing distance is just as important when a vehicle is traveling very far away from the bicycle as when the vehicle is traveling very close. Close events exert a greater aerodynamic force upon the bicycle, and so have greater relevance than very distant passing events.

Another analysis method is to measure the share of events that are above or below a cut-off (such as 1 m) using a logistic regression. However any cutoff chosen can be considered arbitrary, and usually a larger sample size is required to notice any effect. Walker and Robinson (2019) provides a summary of some of the statistical debate surrounding passing distance data in the research to date.

This study presents results from a number of regression models to show that our results are not dependent on the statistical method chosen. We also present results of a quantile regression model, which helps to show that bicycle lanes affect passing distance when cars are overtaking very close to bicycles – but not when they are further away and distance is less relevant.

Table 1
Previous passing distance studies.

Study location	Number of roads measured	Passing events recorded	Distance measurement technology	Reference	Average passing distance	Percent of passes closer than 1 m
UK	6	671	Bike mounted video footage	Parkin and Meyers (2010)	1.1–1.6 m	–
Canada	4	5227	Ultrasonic 10 Hz rack mounted	Mehta et al. (2015)	1.3–2.8 m	.5–12%
New Zealand	6	6268	Lidar sensor	Balanovic et al. (2016)	2.05 m	1.40%
USA	37	568	Bike mounted video footage	Love et al. (2012)	1.45 m	20%
UK	One commute	5690	Ultrasonic 10 Hz mounted low on bike	Walker et al. (2014)	–	24–43%
Taiwan	One commute	1380	Ultrasonic mounted low on the bike	Chuang et al. (2013)	1.68 m	–
USA	One commute	1151	Ultrasonic rack mounted	Chapman and Noyce (2012)	1.95 m	0.50%
Italy	–	468	Driving simulator	Bella and Silvestri (2017)	1.1–1.2 m	–
Sweden	One commute	145	Lidar sensor	Dozza et al. (2016)	1.8–3 m	–
Spain	7	2928	Laser sensor	Llorca et al. (2017)	1.5 m	36%
Australia	unknown	18,527	Ultrasonic 10 Hz Saddle mount	Beck et al. (2019)	1.73 m	5.90%
Australia	unknown	16,476	Ultrasound 20 Hz	Mackenzie et al. (2019)	1.85 m in 60 km/h or less zone	2.7% in 60 km/h or less zone

2. Method

2.1. Defining passing distance

A passing event was defined in this study as any time when a motor vehicle traveling in the closest vehicle lane to the bicycle drove past the bicycle on the right hand side. Events where a motor vehicle changed lanes to overtake the bicycle were considered passing events. Events where a motor vehicle was not travelling in the closest vehicle lane at any point were not considered passing events. Events where the cyclist was passing a vehicle were not considered passing events. Events where the bicycle was stationary were not considered passing events.

Passing distance was defined as the furthermost point to the left on the driver's vehicle to the edge of the bicycle's handlebars. A pass was considered close if the passing distance was less than 1 m for roads with a speed limit of 60 km/h or less, or 1.5 m in the case of roads where the speed limit was greater than 60 km/h. These definitions of passing distance and close passes were adapted from the typical definition in Australian road regulations (e.g. (s 144a Queensland Government, 2009)).

2.2. Quantifying passing distance

Sixteen purpose-built PassBox devices were fabricated to measure passing distance. The devices used two MaxBotix MB1232 I2CXL-MaxSonar-EZ3 ultrasonic sensors reading at 25 samples per second using an Arduino-based board to log distance measurements on both the left hand side and right hand side of the bicycle. This sampling rate was chosen to ensure that at expected differential speeds, the devices would be able to reliably and robustly detect motor vehicles relative to bicycles. The output of a GPS receiver was also logged by the device.

The PassBox device was used in combination with two Garmin Virb X video cameras which each contained a GPS receiver, accelerometer, and gyroscope. One camera was mounted to the front handlebars of the bicycle, facing forward. The rear camera was mounted on top of the PassBox device, facing towards passing traffic to the rear. The PassBox device itself was mounted either on a bicycle rack or from the seat post at a height below 85 cm. While the PassBox device was designed to be discreet, it was visible behind the bicycle and we cannot exclude that it affected drivers' behavior.

The distance measurements taken by the PassBox device were validated by filming a 2013 Toyota Yaris test vehicle being driven over a tape measure repeatedly in a controlled environment. A total of 90 passes were made at speeds of 10 km/h, 30 km/h, and 50 km/h at distances of 50 cm, 100 cm, and 150 cm. The device was found to be accurate to within ±1.8 cm at 50 km/h.

A third-party calibration was also performed by SGS Australia which found the device's measurements fell within ±3 cm of a calibrated Transportable Infra-Red Traffic Logger used for speed enforcement in Victoria, Australia.

Subsequent devices were calibrated by testing against a flat wall at 50 cm, 100 cm, 150 cm, and 300 cm. Sensor readings were not found to vary between devices.

2.3. Study design

A quasi-naturalistic study was conducted to measure passing distances in four Australian cities: Melbourne, Bendigo, Geelong, and Perth. Volunteer cyclists were recruited through Facebook advertising, posters in bicycle shops, and an article in a major Australian newspaper (Carey, 2016).

Laws mandating a minimum distance between cars and bicycles when overtaking were not in force in Melbourne, Bendigo, and Geelong during the study period. Laws mandating 1 m passing distance were introduced in Perth mid-way during the study period.

552 people signed up to participate in the study. Of those, 191 were chosen to ensure a mixture of geographic locations, gender and frequency of cycling trips. 29 participants either failed to cycle during the study period, or experienced device malfunction and could not continue in the study. This left 162 active participants.

The PassBox was fitted to the bicycle either by the study authors or by a trained bicycle mechanic and remained on the bicycle for approximately two weeks for the cyclist's usual trips.

Participants were required to turn on/off the action cameras and PassBox device at the beginning and end of each trip. They were asked to charge front and rear cameras every 1 to 2 days, and the PassBox device weekly, depending on the amount they cycled. The action cameras had a battery life of 90 to 120 min, while the PassBox devices had a battery life of approximately 15 h.

Data were collected between November 2016 and July 2019. Ethics approval was obtained through Curtin University.

2.4. Data reduction

Data was downloaded from the SD cards on the PassBox devices and action cameras by the study authors between each fitting of the devices.

PassBox log files were synchronized to Garmin videos using recorded GPS data. Candidate passing events were identified from the log files via a script that assessed ultrasonic sensor readings. Videos were then created starting 2 s prior and ending two seconds after each candidate passing event. Each video was viewed by a trained research assistant who coded seven variables about each valid passing event:

- the treatment on the left hand side of the bicycle's travelling lane,
- the presence and type of bike lane,
- the number of car lanes on the road,
- the treatment between vehicles travelling in different directions,
- the type of vehicle,
- whether the vehicle changed lanes to overtake, and
- the proximity to and type of intersection.

Bicycle lanes were defined broadly in this study. Australian road rules designate that a bicycle lane must begin and end with a road side sign stating 'bicycle lane' (Levasseur, 2014). Limiting our definition to these bicycle lanes would exclude lanes constructed by local councils that do not meet these guidelines, and would also exclude road shoulders. In this study a bicycle lane was therefore defined as any road area where a bicycle may travel that a vehicle usually would not.

The type of bicycle lanes measured in this study are illustrated in Fig. 1. For statistical analysis, these bike lanes were grouped into four types: protected, wide painted buffer, painted, and no bike lane. Wide painted buffer includes bicycle lanes with painted buffers on either or both sides. Painted includes all other bicycle lane types, except "dotted line" which was assigned to no bicycle lane because vehicles would normally travel in such an area.

Passing events were allocated to bike lane type based on the type of bike lane at the start of each passing event. Therefore one named roadway may have many bicycle lane types. For example, a protected lane might change to green paint near an intersection.

Wing mirrors presented a challenge to accurate collection of data during the study. Wing mirrors are occasionally detected as a sharp change in the distance between the car and the bicycle for a short period during the passing event. The median mirror detected was 11.3 cm wide, found 43% of the way through the event. In Australia, this protrusion is considered part of the vehicle, and must be included in any passing distance calculation. However, for most passing events the ultrasound sensor did not detect the wing mirror. Wing mirrors are much more likely to be detected for taller cyclists, and smaller vehicles. Failure to account for their presence would introduce bias into the study. Therefore a simulated wing mirror of 11.3 cm was inserted 43% of the way through each passing event.

Information about road dimensions was merged from government

Fig. 1. Illustration of bicycle lane types measured.

roads databases and Google Maps. The number of vehicles per day using the road and the speed limit were obtained by merging location and direction of travel from the GPS, accelerometer and gyroscope aboard the Garmin devices with VicRoads databases in Victoria (VicRoads, 2019) and Mainroads databases in Perth (Mainroads (Western Australia), 2019). For example, if a cyclist was heading east then the passing event was matched with an east-west road. This method has the advantage of reducing the error associated with probabilistic matching of noisy GPS data to roads. Where a suitable match could not be made with these databases Google Maps reverse geocoding was used to find the correct road (Google, 2019).

Lane widths were measured by using overhead imagery from Nearmap (2019). Passing events were grouped into road sections by the name of the road, the suburb, the number of vehicle lanes and the bicycle lane type (if present).Passing events in each section were then manually inspected on Nearmap to ensure that widths within that road section were consistent. Road dimensions were then measured using the Nearmap distance tool, which is accurate to ±15 cm. Where manual inspection showed variability in lane widths within a section, road widths were not entered. To reduce data entry time, where less than three passing events were recorded on a road section, lane widths were not entered. 2004 roads sections had lane widths recorded, allocated to 32, 493 passing events.

Lane width is defined in this study as the width of the bicycle lane (if present) and the lane in which the motor vehicle is travelling in. For instance, if a road contains 3 lanes of width 3.5 m and a bicycle lane of width 1.5 m, lane width is $3.5 + 1.5 = 5$ m. If there were no bicycle lane on this road, lane width would be 3.5 m. Roads with no centre line marking were excluded from the study.

Data reduction from log files and videos to candidate passing events was conducted with Python scripts, and statistical analysis on the set of validated and coded passing events was conducted with R (Team R Development Core, 2011) using the tidyverse (Wickham, 2017).

2.5. Statistical modelling

Four statistical models were employed based on different specifications to better understand the relationship between road and traffic attributes and passing distance. Many models were used to ensure that our conclusions are not sensitive to the type of statistical model chosen.

The first model was a fixed effects linear regression of passing distance. This model controlled for whether or not there was a bicycle lane, and if so, the type of bike lane, whether the passing vehicle was a truck, the speed limit, the number of lanes, what was on the footpath side of the cyclist, and the lane width quartile. Cyclist fixed effects were used to control for the fact that some cyclists might be risker riders than others (cycling closer to cars).

The second model was a Bayesian generalized linear regression (a logit specification), which modeled the probability of a pass less than 1 m. It had the same set of controls as the model above, with varying intercepts at the level of the cyclist. The fitted parameters are on the log odds scale.

The third model was a fixed effects linear probability regression, which modeled the probability of a pass less than 1 m. It had the same set of controls as the model above, with cyclist fixed effects. It has the advantage over the second model of having parameters that are easier to

Table 2
Summary of passing events recorded.

Category	Characteristic	*N* (%)	Less than 1 m (%)	Less than 1.5 m (%)	Average passing distance (cm)	Standard deviation (cm)
Vehicle type	Truck, tram or bus	1826 (4%)	7.2	41.8	169	55.5
	Other vehicle	44,943 (96%)	5.9	38.3	171	52.9
Bike lane type	No bike lane	15,001 (32%)	8.2	42.1	168	55.8
	Green paint	1369 (3%)	6.4	42.7	170	58.0
	Dotted line	3133 (7%)	5.9	40.5	169	53.3
	Sharrow	86 (0%)	5.8	30.2	176	51.7
	Footpath side wide painted buffer	523 (1%)	5.5	49.5	159	50.5
	Normal bike lane	23,064 (49%)	5.1	36.9	170	49.8
	Brown paint	2667 (6%)	2.2	32.3	180	52.9
	Traffic side wide painted buffer	584 (1%)	1.5	16.8	207	59.8
	Double wide painted buffer	172 (0%)	0.6	14.5	199	44.6
	Protected	170 (0%)	0.0	5.3	218	56.9
Speed limit	40 km/h or less	3075 (7%)	10.9	48.3	159	54.1
	50 km/h	10,026 (21%)	6.3	40.0	170	54.0
	60 km/h	17,716 (38%)	5.2	38.0	172	53.0
	70 km/h	6541 (14%)	4.2	31.9	177	51.2
	80 km/h	3081 (7%)	4.5	31.2	175	48.2
	90 km/h	187 (0%)	1.1	38.0	170	43.1
	100 km/h	608 (1%)	5.6	27.3	178	48.5
	Speed limit not available	5535 (12%)	7.8	44.2	165	54.0
Width of vehicle lane and bicycle lane (if present)	Less than 3 m	895 (2%)	8.5	42.5	162	49.3
	3 to 3.4 m	3146 (7%)	9.8	44.0	164	54.3
	3.5 to 3.9 m	5181 (11%)	8.0	47.5	162	51.8
	4 to 4.4 m	6564 (14%)	8.9	50.5	158	51.6
	4.5 to 4.9 m	7655 (16%)	3.6	36.3	169	46.2
	5 to 5.4 m	5164 (11%)	2.0	25.1	183	48.2
	5.5 m and above	3873 (8%)	2.8	23.4	189	52.9
	Road dimensions not available	14,291 (31%)	6.4	38.2	173	56.3
Number of vehicle lanes	0	1304 (3%)	4.2	34.4	179	55.1
	1	27,006 (58%)	4.1	34.9	174	50.9
	2	16,703 (36%)	8.5	43.1	166	55.1
	3	1487 (3%)	11.4	51.7	158	56.4
	4 or more	269 (1%)	10.4	44.2	161	53.6
Footpath side of bike lane	A footpath, grass or median	31,140 (67%)	5.4	35.8	173	53.2
	Another lane of vehicle traffic	1648 (4%)	6.9	42.2	168	54.8
	Area for parking – cars present	10,557 (23%)	7.8	47.6	161	50.7
	Area for parking – empty	3424 (7%)	4.6	32.1	177	52.2

interpret, but its statistical properties are not as robust.

The first three models either describe how different road and traffic attributes are associated with an arbitrary 1 m measure of a “close pass,” or the observed differences in the average passing distance. Yet Balanovic et al. (2016) showed that cyclists are much more concerned about marginal differences in passing distances when vehicles are very close than when they are far away.

To account for this, the final model used was a quantile regression model. This model describes the change in the *p*% nearest pass associated with different road and traffic attributes. For example, if $p = 0.1$, the regression describes how many centimeters the 10th percentile of passes changes under different road conditions, on average. The final model has the same set of controls as the first three models, with cyclist fixed effects. The implementation used is described in Koenker (2004).

3. Results

46,769 passing events were recorded during the study by 162 cyclists on 6448 roadway sections.

108 (67%) of cyclists stated that they primarily rode to commute to work or education, with 43 (27%) primarily cycling for recreation and the remainder for other activities. 86 (53%) rode on road bikes, 32 (20%) rode bikes with less aggressive geometry such as touring or flat bar road bikes, 11 (7%) ebikes, and the remainder split between step through, mountain bike and other. Their median age was 43. 42 (25.9%) were female.

A map with a video of each passing event is available at http://www.passbox.org/map.

3.1. Distribution of passing events

Table 2 shows the number of passing events, average passing distance and number of close passes by road condition. There was a wide distribution, but the majority of passing events occurred on roads with speed limits 60 km/h or less (76.2%) and a bicycle lane (67.9%).

2777 (5.9%) passing events were less than 1 m and 17,970 (38.4%) were less than 1.5 m as shown in Fig. 2. For passing events in speed limit zones 60 km/h or less, 1931 (6.14%) were less than 1 m, and for events in speed limit zones 70 km/h or more 3120 (31.8%) were less than 1.5 m.

3.2. Lane width

On wider roads, vehicles tended to give cyclists more space when overtaking. Where the total width of the first vehicle lane and the bicycle lane (if present) was wider than 5 m – only 2.33% of passing events occurred at less than 1 m. On narrow lanes less than 3.5 m, 9.11% of passing events were closer than 1 m.

These findings were robust to our regression analysis (see Table 3). Roads were grouped into four equal categories based on the total width of the first vehicle lane and the bicycle lane (if present). These groups were between 2.5, 3.7, 4.5, 5, and 7.6 m. After controlling for the factors listed in Fig. 3, wider roads tended to have 16.9 cm wider average passing distances (left panel), and 4.84% fewer passing events were less than 1 m (right panels).

3.3. Vehicle type

Larger vehicles, especially buses, tended to give less space. Fig. 4 shows that buses passed closer than 1 m 8% of the time, while sedans passed close only 6% of the time. Trucks passed closer than 1 m 6% of the time – a similar amount as smaller cars. However trucks tended to pass on roads that had much more space to overtake. The average truck overtook on a road 4.66 m wide, and the average sedan 4.58 m wide.

The regression models in Fig. 3 shows that, after controlling for other factors, a truck, tram or buses tended to overtake 16.9 cm closer (left panel), and they were 4.84% more likely to pass closer than 1 m (right panels).

Only 31 emergency services vehicles were recorded in our study, and 4 of them passed closer than 1 m.

3.4. Speed limit

On higher speed roads, vehicles tended to give cyclists more space. This extra space, however, is not enough to overcome the extra aerodynamic forces exerted on cyclists at higher speeds. Table 2 shows that on roads 40 km/h or less, 10.9% of vehicles passed closer than 1 m, but on roads 80 km/h 4.5% passed close. However, the percentage of

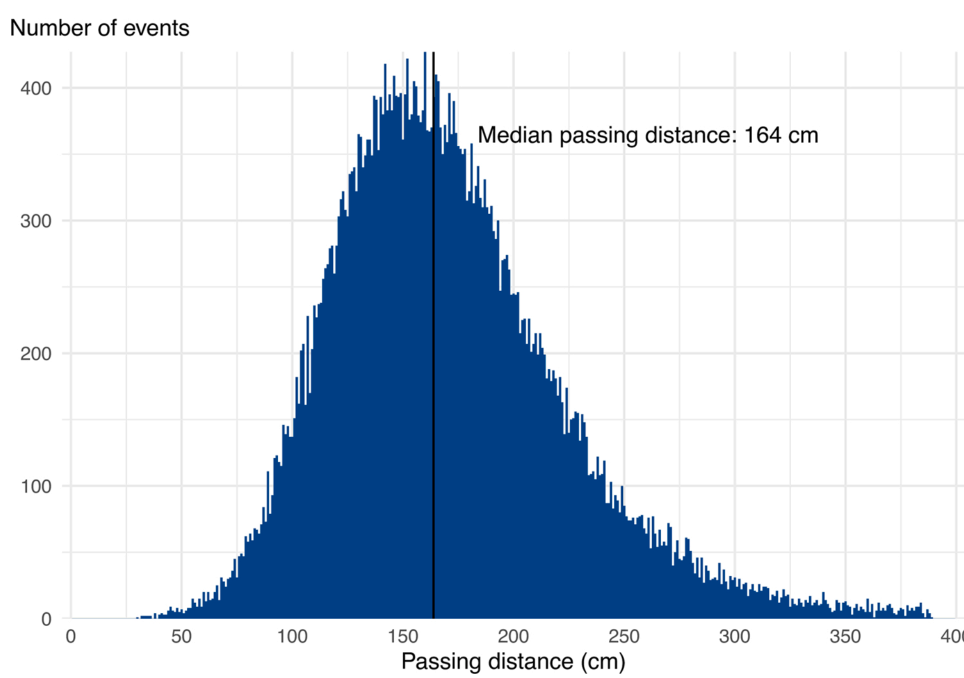

Fig. 2. Histogram of passing distance.

Table 3
Results from Bayesian: Bayesian generalized linear regression (logit specification), Distance: fixed effects linear regression, and 1 m: fixed effects linear probability regression

Variable	Level	Estimate	Std Err	*p*-Val	Confidence interval		Model
					Lower	Upper	
Bike lane	Painted	−0.388	0.076	NA	−0.539	−0.238	Bayesian
		1.377	0.837	0.100	−0.263	3.017	Distance
		−1.747	0.388	0.000	−2.508	−0.986	1 m
	Protected	−4.017	1.446	NA	−7.442	−1.804	Bayesian
		53.019	5.929	0.000	41.398	64.640	Distance
		−16.597	2.757	0.000	−22.001	−11.193	1 m
	Wide painted buffer	−1.852	0.473	NA	−2.928	−0.995	Bayesian
		30.256	2.807	0.000	24.755	35.757	Distance
		−5.815	1.306	0.000	−8.375	−3.256	1 m
Intersection	Intersection	0.191	0.080	NA	0.038	0.348	Bayesian
		3.816	1.063	0.000	1.732	5.899	Distance
Period	Peak hour	0.134	0.067	NA	0.000	0.258	Bayesian
		−0.900	0.737	0.222	−2.345	0.545	Distance
		0.814	0.343	0.018	0.142	1.486	1 m
Speed limit	70 km/h or more	−0.523	0.083	NA	−0.684	−0.369	Bayesian
		7.177	0.852	0.000	5.507	8.848	Distance
		−2.609	0.396	0.000	−3.385	−1.833	1 m
Vehicle lanes	No centre line marking two or more lanes	−0.244	0.246	NA	−0.753	0.206	Bayesian
		11.203	2.100	0.000	7.087	15.318	Distance
		−1.097	0.977	0.261	−3.011	0.817	1 m
		0.780	0.073	NA	0.635	0.924	Bayesian
		−7.495	0.792	0.000	−9.047	−5.942	Distance
		4.141	0.368	0.000	3.421	4.862	1 m
Vehicle size	Truck, tram or bus	0.271	0.122	NA	0.034	0.496	Bayesian
		−1.823	1.430	0.202	−4.626	0.980	Distance
		1.494	0.665	0.025	0.191	2.798	1 m
Width of vehicle and bike lane (quartile)	2	−0.156	0.079	NA	−0.312	−0.006	Bayesian
		0.831	0.974	0.394	−1.078	2.740	Distance
		−1.081	0.453	0.017	−1.969	−0.193	1 m
	3	−0.739	0.099	NA	−0.932	−0.549	Bayesian
		5.394	1.081	0.000	3.275	7.513	Distance
		−4.353	0.503	0.000	−5.339	−3.368	1 m
	4	−1.040	0.107	NA	−1.247	−0.831	Bayesian
		16.858	1.039	0.000	14.821	18.895	Distance
		−4.841	0.483	0.000	−5.789	−3.894	1 m

vehicles that traveled within 1.5 m on 80 km/h roads was very high, 31.2%.

The regression models in Fig. 3 shows that, after controlling for other factors, on roads with a speed limit of 60 km/h or less vehicles tended to overtake 7.18 cm closer (left panel), and were 2.61% more likely to pass closer than 1 m (right panels).

3.5. Multi-lane roads and busy roads

On multi-lane roads, vehicles tended to give cyclists less space. Multi-lane roads had a close passing risk of 8.8%, compared to 4.1% for single lane roads.

Within single lane roads, roads without a divider also had a high share of close passes, (Fig. 5), but this can be explained by the fact that these passing events tended to be narrow local roads. Other road separators had no statistically significant effect on passing distance.

Multi-lane roads tend to be busy, but busy roads were not found to affect passing distance on their own. Roads were grouped into five equal categories based on the number of vehicles per day per traffic lane as recorded by government databases of road congestion VicRoads (2019) and Mainroads (Western Australia) (2019). The quietest quintile (less than 8295 vehicles per lane per day) had 6.6% of passes less than 1 m, while the busiest (greater than 17,000 vehicles per lane per day) had 6.3%.

The results presented so far have examined the likelihood that a vehicle will pass close to a bicycle. The likelihood that a cyclist will experience a close pass can also be assessed by measuring the number of close passes a cyclist will experience in a given trip.

Fig. 6 shows that for trips with more than 200 passing events, 100 per cent had at least one close pass. Close passing was much more common on roads with higher traffic, and so the overall risk of being passed closer on a busy road was high.

3.6. Parked cars

When parked cars were present, vehicles tended to give cyclists less space. Table 2 shows that on roads with parked cars, 7.8% of vehicles passed closer than 1 m, but when the cyclist was next to a footpath, 5.4% passed close.

Fig. 7 shows that on narrow roads, close passing is much more common when parked cars are present. For lanes wider than 2.5 m, parked cars no longer offer any disadvantage.

The regression models in Fig. 3 show that, after controlling for other factors, vehicles tended to overtake cm closer on roads with parked cars than those with no parking (left panel), and were % more likely to pass closer than 1 m (right panels).

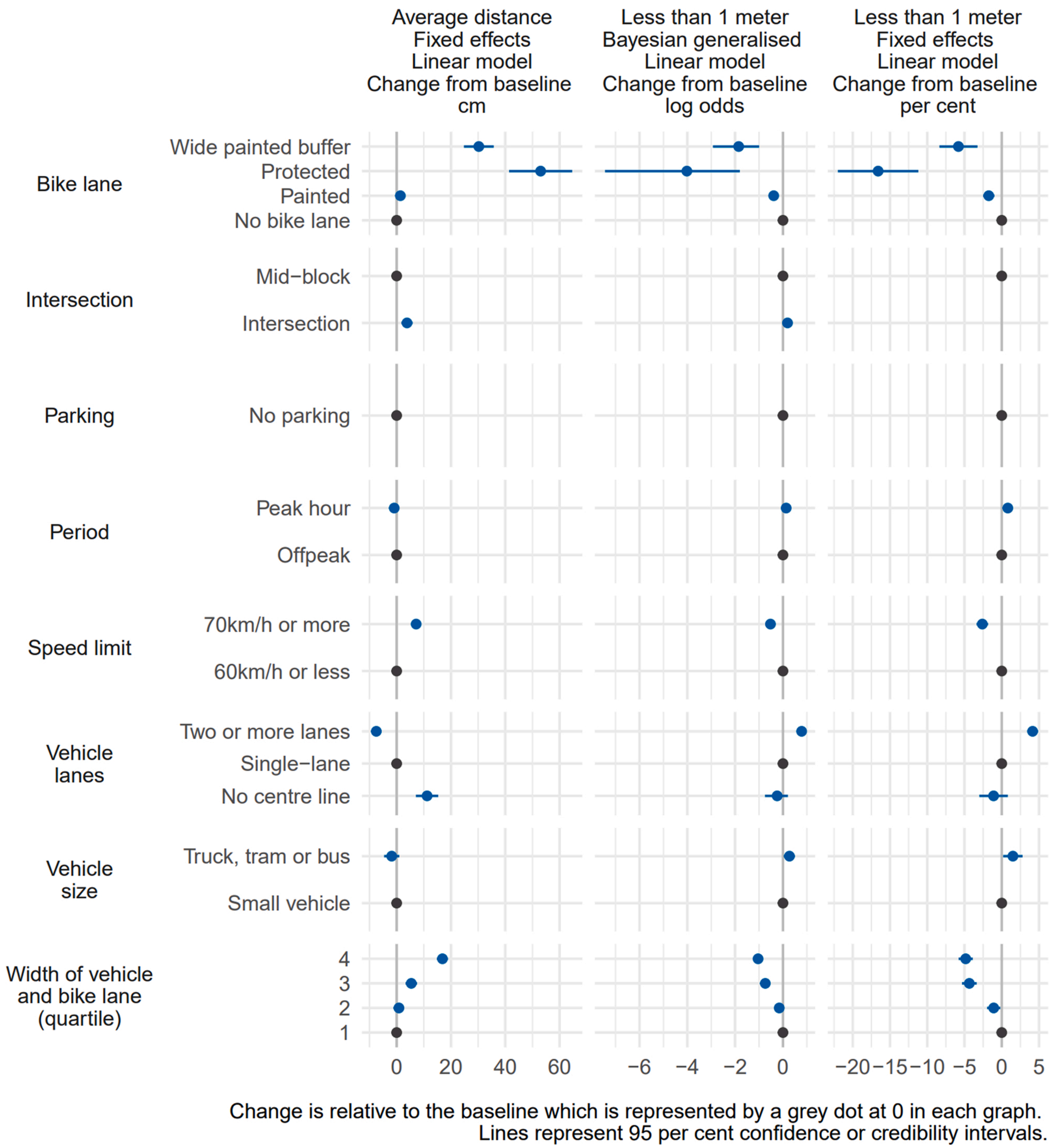

Fig. 3. Factors that predict passing behaviour – regression outputs for 3 models.

3.7. Bicycle lanes

When a bicycle lane was present, vehicles tended to give cyclists more space.

Fig. 8 shows that for wide roads, the effect of a bicycle lane on close pass risk was strong. The effect of a bicycle lane along a narrow (between 3.5 and 4.5 m) roadway was less strong. However the standard deviation of average passing distance was lower on roads with a bicycle lane (48.8 cm), than without (54 cm) suggesting that bicycle lanes reduced the variation and unpredictability of vehicle behavior, even on narrow roads.

Not all bicycle lanes are equal: Fig. 9 shows that passing events on roads with wider bicycle lanes and bicycle lanes that offer more protection were much less likely to be close. 170 events were recorded on roads with bicycle lanes with a raised buffer between the bicycle and the vehicle (otherwise known as a 'protected' bicycle lane). None of these events had a passing distance less than 1 m.

Bicycle lanes with a wide painted buffer between the bicycle lane and the vehicle lane also experienced a low rate of close passing events. 756 passing events were recorded on roads with a wide painted buffer, and 1.32% were less than 1 m.

The cities sampled had several off road bicycle tracks and bicycle lanes where cyclists were protected from motor vehicles by car parking. No passing events were recorded on these road sections, and therefore

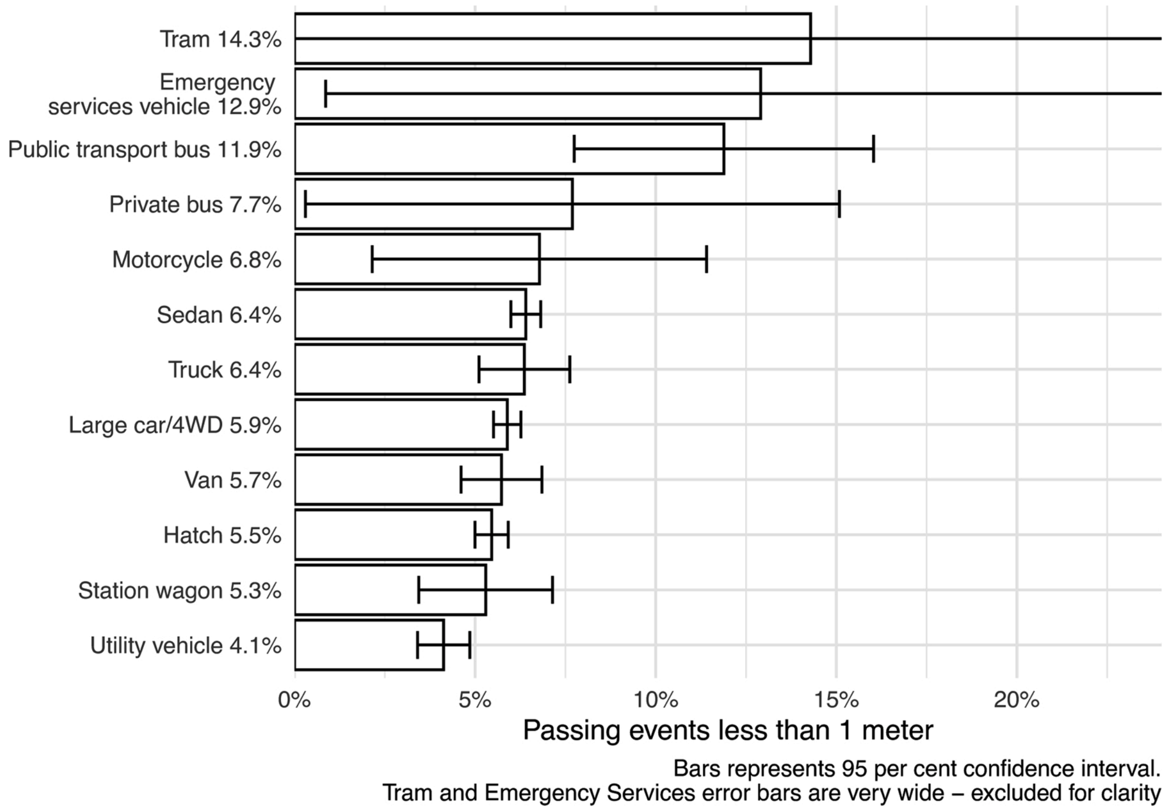

Fig. 4. Vehicle type and close pass rate.

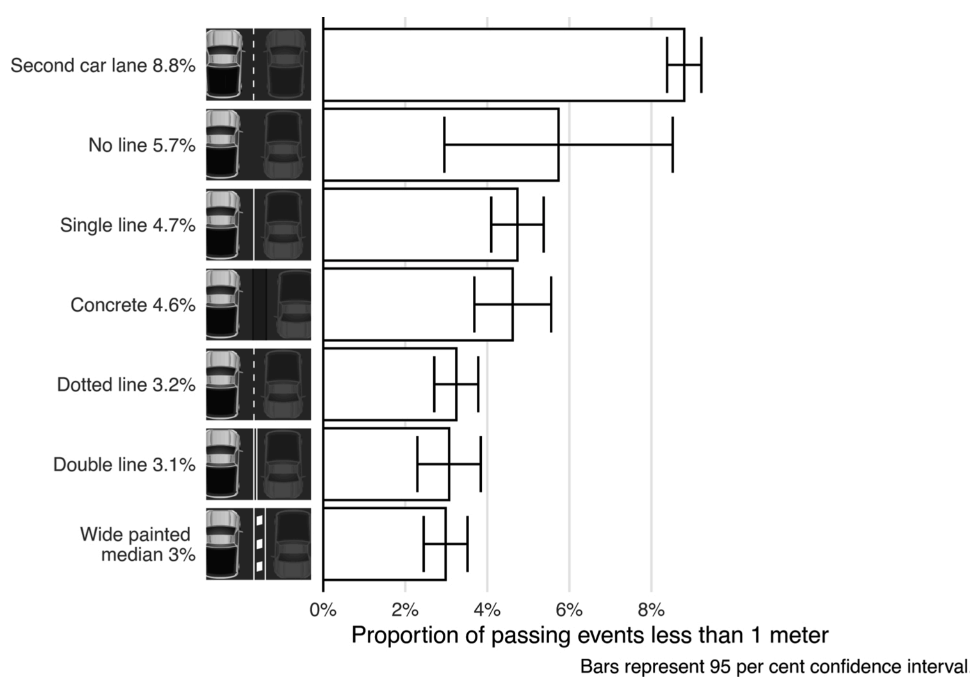

Fig. 5. Proportion of passes less than 1 m by treatment on the traffic side of the motor vehicle.

none were close.

The regression models in Fig. 3 show that, after controlling for other factors, on roads with painted bicycle lanes, vehicles tended to overtake 1.38 cm further away than on roads without a bike lane (left panel), and were 1.75% less likely to pass closer than 1 m (right panels).

On roads with wide painted buffers, vehicles tended to overtake 30.3 cm further away than on roads without a bike lane, and were 5.82% less likely to pass closer than 1 m.

On roads with protected bicycle lanes, vehicles tended to overtake 53 cm further away than on roads with no bicycle lanes, and were 16.6% more likely to pass closer than 1 m (right panels).

The *p*-value for average passing distance was 0.1, which is well above common cut-offs for significance. This result therefore warranted more investigation.

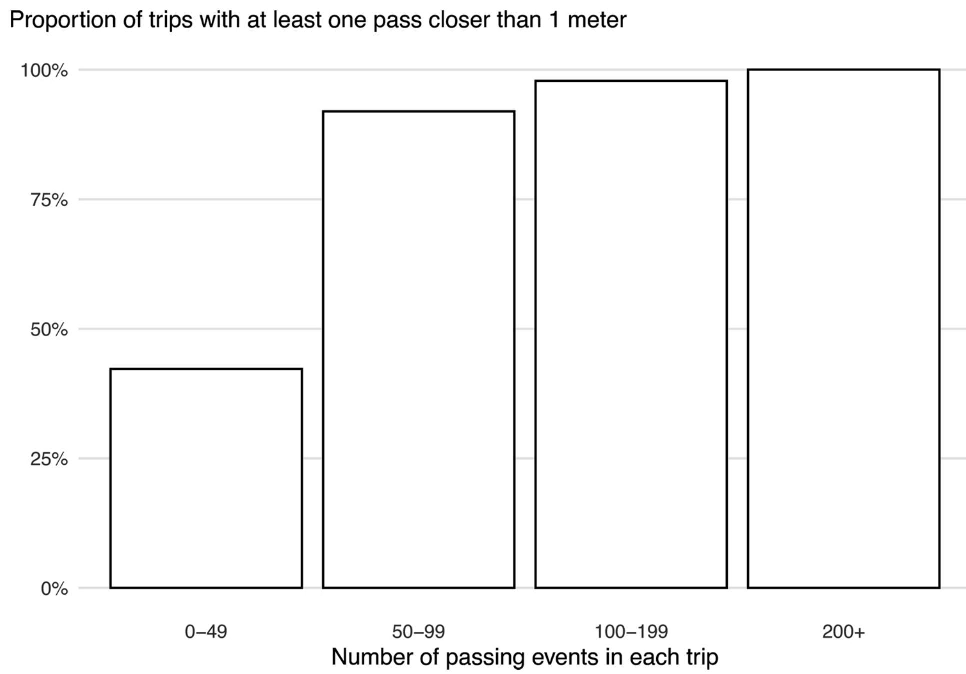

Fig. 6. Proportion of trips that involve at least one passing event closer than 1 m.

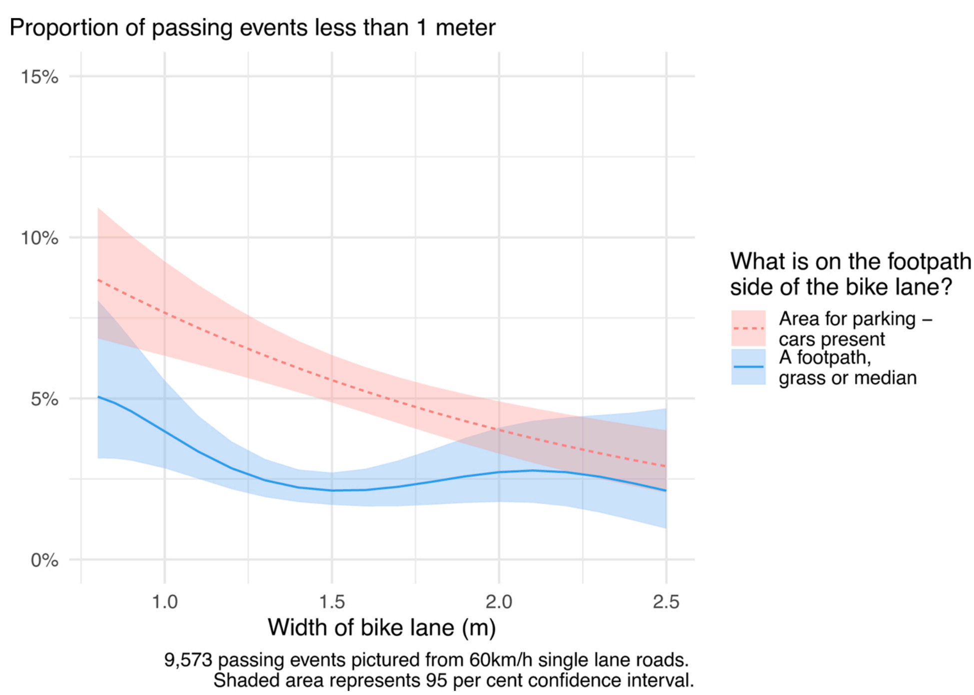

Fig. 7. Proportion of passes less than 1 m by bike lane width.

To understand the findings above, Fig. 10 illustrates the effects on passing distance for the four categories of bike lanes from a quantile regression, with results listed in Table 4. Protected bicycle lanes and bicycle lanes with wide painted separators have large effects across the distribution of passing distances, but painted bicycle lanes only have a positive influence at very close distances. Controlling for the variables listed in Fig. 3, the 5th percentile of passing distance on a road without a bicycle lane is 93.3 cm. The 5th percentile on a road with a painted bicycle lane is 101 cm – 8.1% higher. For protected lanes, the 5th percentile is 166 cm – 78% higher.

Consistent with the findings of the Bayes and logit models in Fig. 3, the quantile regression finds that protected bicycle lanes are associated with a 10 times greater increase in passing distance than painted bicycle lanes at the 5th percentile.

Painted bicycle lanes only show a significant improvement in passing distance at very close percentiles. Where cars are further away and it matters less, there is no change in passing behavior.

4. Discussion

This study shows that the best way to reduce the risk of motor vehicles passing bicycles too close is to provide a protected bicycle lane. No

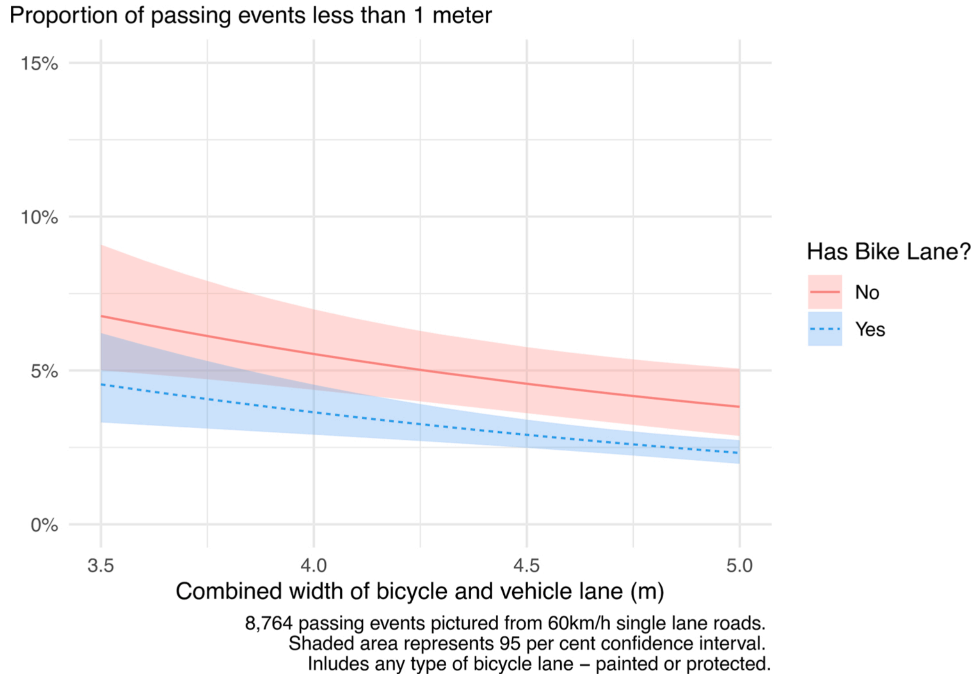

Fig. 8. Proportion of passes less than 1 m by width of bicycle lane and vehicle lane.

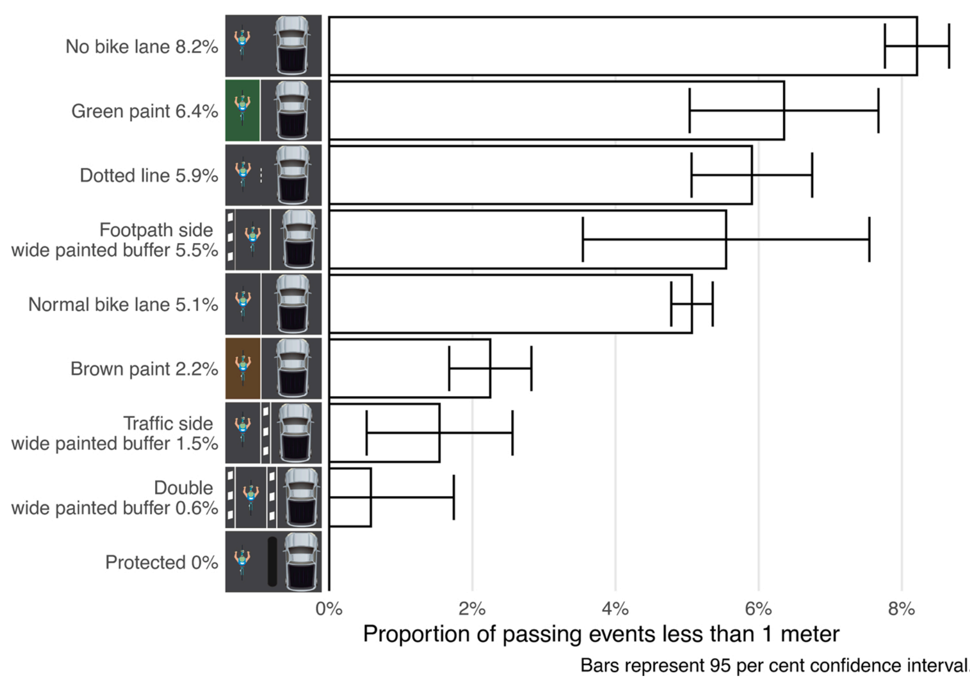

Fig. 9. Proportion of passes less than 1 m by bicycle lane type.

passing events closer than 1 m were recorded in protected bicycle lanes.

While other road treatments can significantly reduce the risk of a motor vehicle passing a bicycle too close, the risk of a cyclist experiencing a close pass on a given trip is mainly dependent on the number of drivers who overtake the cyclist. Even if close passing is not very common, a cyclist traveling on a busy road without a protected bicycle lane is likely to experience a close pass.

If for technical or political reasons it is not feasible to put a protected bicycle lane on a particular road, a painted bicycle lane is the best alternative for reducing the proportion of events that are close. A wide bicycle lane with a wide painted buffer between the cyclist and traffic can reduce the risk of a pass less than 1 m significantly when compared to a similar road with a regular painted bicycle lane or a no bicycle lane at all. Narrowing the traffic lane to 2.6 m or lower should be considered on roads with speed limits up to 60 km/h, with a wide painted separator provided for overhang by oversized vehicles.

Australian road design guidelines (Levasseur, 2014) have provision for “wide kerbside lanes” with a desired minimum of 4.2 m, to allow vehicles to overtake bicycles without changing lanes. Any lane of this width would have a lower incidence of close passing events if a bicycle lane were painted. While a protected lane is preferred, a painted bicycle lane is much better than a wide kerbside lane at reducing the incidence

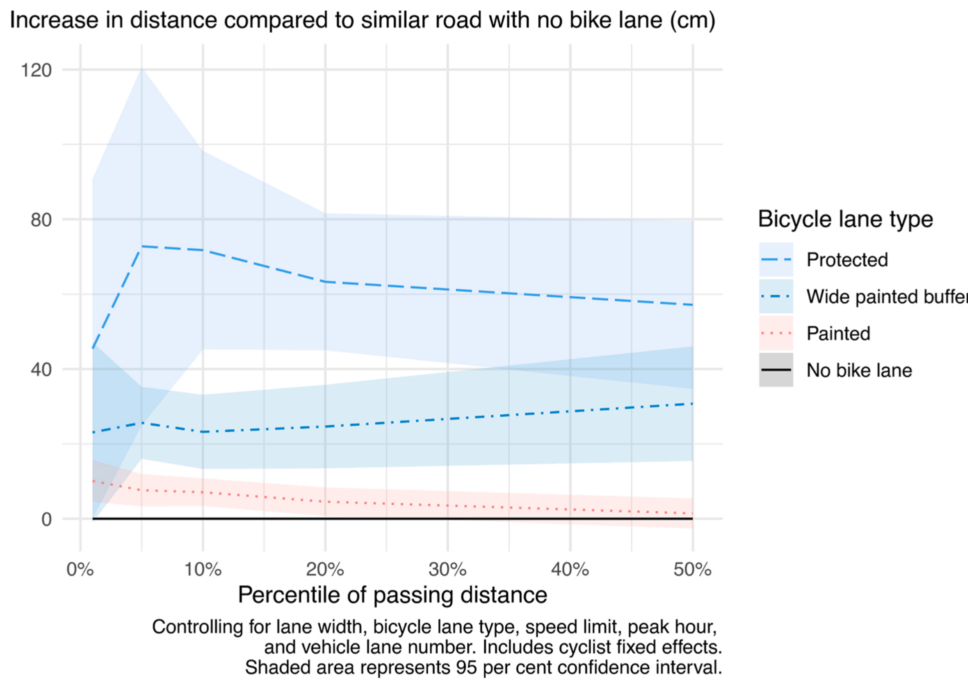

Fig. 10. Quantiles of passing distance by bicycle lane type – relative to no bicycle lane.

Table 4
Quantile regression results, with estimates of passing distance (cm).

Bicycle lane type	Quantile	Estimate	Std Error	Confidence interval	
				Lower	Upper
Protected	0.01	114.9	23.09	69.7	160.2
Wide painted buffer		92.5	12.25	68.5	116.5
Painted		79.6	2.82	74.0	85.1
No bike lane		69.5	3.75	69.5	69.5
Protected	0.05	166.1	24.39	118.2	213.9
Wide painted buffer		118.9	4.88	109.3	128.5
Painted		100.9	2.19	96.6	105.2
No bike lane		93.3	2.37	93.3	93.3
Protected	0.10	177.5	13.51	151.1	204.0
Wide painted buffer		129.0	5.05	119.1	138.9
Painted		112.9	1.87	109.2	116.5
No bike lane		105.8	2.57	105.8	105.8
Protected	0.20	192.3	9.32	174.1	210.6
Wide painted buffer		153.7	5.68	142.5	164.8
Painted		133.6	1.93	129.8	137.4
No bike lane		129.0	2.29	129.0	129.0
Protected	0.50	216.7	11.43	194.3	239.1
Wide painted buffer		190.3	7.79	175.0	205.6
Painted		161.0	2.02	157.1	165.0
No bike lane		159.6	2.34	159.6	159.6

of close passing.

Bicycle lanes next to parked cars are less effective at reducing close passing events than bicycle lanes next to the footpath. Australian road guidelines recommend a desirable width for a painted bicycle lane of 1.5 m at 60 km/h. 1.5 m is insufficiently wide to minimize passing events closer than 1 m in a bicycle lane next to parked cars. A bicycle lane of at least 2.3 m width including a wide painted buffer is much more effective at reducing the incidence of passing events less than 1 m. However if more than 2.0 m of road width is available, passing distances will almost always be wider with a protected bicycle lane on the footpath side of parked cars instead of a traffic side bicycle lane.

The number of vehicles per day that use a road was found to have no effect on passing distance. Research summarised in (Rubie et al., 2020) shows that vehicles are more likely to pass close when there is oncoming or adjacent traffic. This paper did not measure oncoming or adjacent traffic, but the absence of an effect of vehicles per day on passing distance tends to suggest that if such traffic is a significant factor, it is because some drivers choose to overtake cyclists when vehicles are in other lanes, rather than because some lanes are more likely to have adjacent or oncoming vehicles.

Roads with two lanes of traffic traveling in the same direction as the cyclist have significantly higher incidence of close passing than single lane roads. This may be the case because it is more difficult to perform a head check and change lanes to overtake than it is to look forward into oncoming traffic. Multi-lane roads should be considered particularly prone to close passing events, and more effort should be made to provide a protected bicycle lane on such roads.

Prior research on whether bicycle lanes reduce close passing events (discussed in the Introduction) has been equivocal. Measuring passing distances across many roadways and participants is not easy. The passing distance device must be correctly placed on the bicycle and calibrated to detect passing events accurately. Each roadway has a large number of factors that could affect passing distance, including roadway width. These factors must be recorded in order to reach accurate conclusions.

The model chosen to measure the effectiveness of road attributes is crucial to reach accurate conclusions. Some road attributes such as a regular painted bicycle lane are effective at reducing very close passing events, but not effective at changing events that are far away from the bicycle. Passing events that are very close are of more concern to cyclists, and therefore studies in this field should consider quantile regression where possible.

This study found that roads with painted bicycle lanes reduce close-passing compared to roads with no bicycle lane, albeit by a small amount. This contradicts the finding of Beck et al. (2019). Beck et al. (2019)'s findings can be attributed to deficiencies in their study design (as discussed in the introduction), and the specification of their model, which did not account for important factors such as lane width. The study presented here overcomes many of the limitations in Beck et al. (2019), and therefore the results of this study should be favored.

5. Future work

5.1. Effectiveness of minimum passing distance laws

There is much conjecture about the possible effectiveness of laws requiring motor vehicles to leave a minimum distance when passing bicycles. The PassBox dataset collected in Perth, Western Australia will allow future studies to assess the effectiveness of these laws.

5.2. Cyclist lane positioning

The PassBox dataset has also collected passing distance data on the left hand side of the bicycle (the footpath side), however this has not been used in the current analysis. Future work may explore the influences of cyclist positioning within the lane (with or without a bike lane present). This may assess the relationship between passing distance and a cyclist's lateral positioning in the lane, and the incidence of cycling in the car door zone. As single-bicycle crashes resulting in fatalities are occurring with increasing incidence (Schepers et al., 2017), infrastructure design factors may be able to be identified that help minimise the chance of the cyclist riding too close to the verge, which may contribute to such crashes.

5.3. Speed, passing distance, and cyclist experience

An important dimension of bicycle overtaking that has not been addressed in this work is the actual speed of the overtaking vehicle. While our analysis used location data to determine the speed limit on the road, the PassBox device is not able to directly measure the speed of the vehicle. Close passes at high speed (and particularly from large vehicles) exert substantial lateral aerodynamic force on cyclists (Ferrara, 2001), both affecting cyclist stability and tending to scare the cyclist (Balanovic et al., 2016). The authors expect that close passes at low speed may not tend to discourage cycling, and may pose a very small risk of injury or fatality, while close passes at high speed are likely to discourage cycling and carry a high risk of injury or fatality. Assessing the impact of passing distance in combination with vehicle speed could be combined with fatality and injury risk curves (e.g. (Rosén and Sander, 2009)) to help improve design guidelines for safe infrastructure.

Another dimension of bicycle overtaking that has not been addressed in this work is the cyclist's experience of an overtake. Understanding the cyclist experience as related to the combination of speed and passing distance would also help to predict how infrastructure improvements may improve cycling participation.

6. Conclusion

The largest on-road passing distance study to date was conducted in cities around Australia, yielding 46,769 passing events from 162 cyclists. Statistical modeling has shown that the strongest predictors of a close passing event were roads with on street parking, two or more traffic lanes, or an overtake by a large vehicle. The strongest protective factors were wider roadways and bicycle lanes.

Protected bicycle lanes completely remove the risk of close passing events. Where it is not possible to build a protected bicycle lane it is preferable to have a painted bicycle lane than no bicycle lane at all.

Credit author statement

Jonathan Nolan: Conceptualization, Methodology, Software, Validation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project administration, Formal analysis.

James Sinclair: Conceptualization, Methodology, Software, Validation, Data Curation, Writing – Review & Editing.

Jim Savage: Visualization, Formal analysis.

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Conflict of interest

Consistent with the AAP fact sheet surrounding conflict of interest declarations, the authors of this article would like to declare that the research for this article received funding by the Victorian Transport Accident Commission.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.aap.2021.106184.

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