1   **How much space do drivers provide when passing cyclists? Understanding the impact of motor**
2   **vehicle and infrastructure characteristics on passing distance**

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4   Ben Beck[a], Derek Chong[b], Jake Olivier[c,d], Monica Perkins[a], Anthony Tsay[a], Adam Rushford[a],

5   Lingxiao Li[e], Peter Cameron[a,f,g], Richard Fry[h], Marilyn Johnson[j,k]

6

7   a.   Department of Epidemiology and Preventive Medicine, Monash University, Victoria,
8   Australia
9   b.   Faculty of Science, The University of Melbourne, Victoria, Australia
10 c.   School of Mathematics and Statistics, University of New South Wales, New South
11   Wales, Australia
12 d.   School of Aviation, Transport and Road Safety (TARS) Research Centre, University of
13   New South Wales, Sydney, Australia
14 e.   Faculty of Information Technology, Monash University, Victoria, Australia
15 f.   Emergency and Trauma Centre, The Alfred, Melbourne, Victoria, Australia
16 g.   National Trauma Research Institute, Victoria, Australia
17 h.   Health Data Research UK, Swansea University Medical School, Swansea University, UK
18 i.   Institute of Transport Studies, Faculty of Engineering, Monash University, Victoria
19   Australia
20 j.   Amy Gillett Foundation, Victoria, Australia

21

22 **Corresponding author:**

23 Ben Beck
24 School of Public Health and Preventive Medicine, Monash University, Australia
25 Faculty of Medicine, Nursing and Health Sciences
26 553 St Kilda Rd, Melbourne, VIC 3004
27 Telephone: +61 3 9903 0316
28 Email: ben.beck@monash.edu

29

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31   **ABSTRACT:**

32   **Background:** Understanding factors that influence the distance that drivers provide when passing

33   cyclists is critical to reducing subjective risk and improving cycling participation. This study aimed to

34   quantify passing distance and assess the impact of motor vehicle and road infrastructure

35   characteristics on passing distance.

36   **Methods:** An on-road observational study was conducted in Victoria, Australia. Participants had a

37   custom device installed on their bicycle and rode as per their usual cycling for one to two weeks. A

38   hierarchical linear model was used to investigate the relationship between motor vehicle and

39   infrastructure characteristics (location, presence of on-road marked bicycle lane and the presence of

40   parked cars on the kerbside) and passing distance (defined as the lateral distance between the end

41   of the bicycle handlebars and the passing motor vehicle).

42   **Results:** Sixty cyclists recorded 18,527 passing events over 422 trips. The median passing distance

43   was 173cm (Q1: 137cm, Q3: 224cm) and 1,085 (5.9%) passing events were less than 100cm. Relative

44   to sedans, 4WDs had a reduced mean passing distance of 15cm (Q1: 12cm, Q3: 17cm) and buses had

45   a reduced mean passing distance of 28cm (Q1: 16cm, Q3: 40cm). Relative to passing events that

46   occurred on roads without a marked bicycle lane and without parked cars, passing events on roads

47   with a bike lane with no parked cars had a reduced mean passing distance of 27cm (Q1: 25cm, Q3:

48   29cm), and passing events on roads with a bike lane and parked cars had a mean lower passing

49   distance of 40cm (Q1: 37cm, Q3: 43cm).

50   **Conclusions:** One in every 17 passing events was a close (<100cm) passing event. We identified that

51   on-road bicycle lanes and parked cars reduced passing distance. These data can be used to inform

52   the selection and design of cycling-related infrastructure and road use with the aim of improving

53   safety for cyclists.

54

INTRODUCTION

56 Cycling as an active mode of transport has numerous health, environmental and social benefits. [1-3]

57 For example, commuting by bicycle is associated with a 41% lower risk of all-cause mortality and

58 45% lower risk of cancer incidence.[2] However, cycling injuries are on the rise[4] and a large proportion

59 of these involve collisions with motor vehicles.[5]

60 To increase participation, there is a need to address key barriers to cycling. Prior studies have noted

61 that traffic conditions and motor vehicles driving closely to cyclists heighten subjective risk and

62 create a barrier to cycling participation.[6-9] Therefore, quantifying how close motor vehicles pass

63 cyclists and identifying the characteristics of close passing events provides an opportunity to develop

64 interventions that address key barriers to increased cycling participation. Prior studies of passing

65 distance have typically been conducted using a single instrumented bicycle on a set route,[10-13] using

66 data collected only on a single cyclist,[14] or have used a limited number of fixed traffic cameras to

67 estimate passing distance,[15] thus limiting the generalisability of these findings. Naturalistic driving

68 studies have also been used to study the lateral distance that vehicles provide when passing cyclists,

69 but have been limited to a small number of passing events,[16] or have used surrogate measures of

70 passing distance, such as the distance to the bicycle lane marking, rather than quantifying lateral

71 passing distance.[17] Using a device that can be fitted to any bicycle and enabling cyclists to self-select

72 their route may alleviate some of the limitations of prior studies. To address this knowledge gap, we

73 developed a purpose-built, on-bike device that measures the distance that motor vehicles provide

74 when passing cyclists. Using this technology, this study aimed to quantify passing distance and

75 assess the impact of motor vehicle and road infrastructure characteristics on passing distance.

76

METHODS

Study design

79 An on-road observational study was conducted in Victoria, Australia. A screening survey was used to

80 identify potential participants. Eligible participants provided consent to be involved in the study, had

81 a custom device installed on their bicycle and rode as per their usual cycling for one to two weeks.

82 Data collection occurred between April and August 2017.

83 **Ethics**

84 Ethical approval for the study was obtained from the Monash University Human Research Ethics

85 Committee (CF16/2348 – 2016001181).

86 **Inclusion criteria**

87 A screening survey was used to identify eligible participants. The screening survey was promoted

88 through Monash University social media accounts. The screening survey asked about age, sex,

89 bicycle type, cycling experience, percentage of a usual ride spent on-road, number of times riding a

90 bicycle per week, purpose of the majority of riding and geographical region. Based on this

91 information, purposive sampling was used to recruit cyclists who rode mostly on-road (>60% of an

92 average trip), were located in metropolitan Melbourne (and distributed across metropolitan

93 Melbourne) and rode more than two times per week.

94 **Quantifying passing distance**

95 A purpose-built, on-bike device was developed for the purposes of this study. This device, named the

96 MetreBox, utilised the following technology: Adruino microprocessor (Adafruit Feather M0

97 Adalogger); Global Positioning System (GPS) sensor (Adafruit Ultimate GPS FeatherWing) that

98 recorded at 1 Hz; ultrasonic sensor (XL-MaxSonar-EZ3 MB1230, Maxbotix, Minnesota, USA) that

99 recorded at 10 Hz; and lithium ion 18650 hard case battery with voltage protection (Core

100 Electronics).

101 A custom designed hard case was created with a 3D printer. The device was charged using a micro

102 USB cable and data were stored on a micro SD card. Validation of the ultrasonic sensor was

103   performed using a flat wall and each MetreBox was tested at 100cm and 200cm ranges, accuracy of

104   each individual sensor varied. Each MetreBox was individually tested and calibrated, resulting in a

105   measurement accuracy of +/- 1.5cm. The device had a measurement range of 0cm to 330cm.

106   *Device installation*

107   Device installation was performed by a study research assistant. The MetreBox device was installed

108   on each participant's own bicycle under the saddle and a forward facing GoPro Hero 5 Session

109   (GoPro, California, USA) was mounted on the handlebars (Figure 1). Each participant was provided

110   with a detailed user guide and was responsible for activating both the MetreBox and GoPro camera

111   at the start of each ride. Both devices recorded constantly. The study research assistant measured

112   the width of the handlebars. The end of the handlebar was deemed to be the widest point on the

113   bicycle. Consistent with prior studies,[18,19] the passing distance was calculated as the distance from

114   the end of the handlebars to the passing motor vehicle.

115   **Procedures**

116   *Defining passing event*

117   A passing event was deemed to occur when a motor vehicle passed a cyclist within the recordable

118   range of the MetreBox device. Thus, events in which a cyclist undertook a motor vehicle were

119   excluded. Additionally, events in which a cyclist passed another cyclist were excluded. As per

120   legislation in most Australian jurisdictions,[20] a 'close' passing event was deemed to be an event with

121   a passing distance less than one metre. In Australia, vehicles drive on the left and hence, in this

122   study, we have quantified passing events occurring to the right of the cyclist.

123   *Coding passing events*

124   A manual review of all recorded events was undertaken by two coders who were trained prior to the

125   commencement of coding. This review was firstly used to exclude passing events that were not

126   motor vehicles or events in which a cyclist undertook a motor vehicle. Secondly, characteristics of

127   each event were classified. These characteristics were defined *a priori* using the Cycling Aspects of

128   Austroads Guide[21] as a reference. These were:

129   •   Vehicle type (sedan, taxi, four-wheel drive (4WD), truck, bus, motorcycle, other)

130   •   Location (mid-block, intersection, roundabout)

131   •   On-road marked bicycle lane (present, absent)

132   •   Parked cars on the kerbside (present, absent)

133   An on-road marked bicycle lane was coded when there was a marked dedicated space for cyclists. A

134   random selection of ten rides were independently coded by two coders and the inter-rater reliability

135   was assessed (see Statistical analyses below).

136   ***Map matching, speed zones and road types***

137   To be able to map known locations of passing events to speed zone data, GPS data were aligned to

138   road network maps (OpenStreetMap, OpenStreetMap contributors, 2015. Retrieved from

139   https://planet.openstreetmap.org). This was achieved using a probabilistic map matching approach

140   and implemented in Python using the ST-matching method.[22,23] Speed zone data were obtained from

141   VicRoads' open source shapefile available on data.vic.gov.au.[24]

142   To quantify the distance that cyclists travelled on-road (and were therefore exposed to motor

143   vehicles), GPS traces were map matched to the OpenStreetMap road and cycle network maps using

144   Python and a modified version of the Open Source Routing Machine (ORSM; http://project-

145   osrm.org/) Map Matching service. OpenStreetMap road classifications were used to classify

146   segments that were on-road (e.g. 'motorway', 'primary', 'residential') and segments that were off-

147   road (e.g. 'cycleway', 'path').

148   **Statistical analyses**

149   Agreement between coders was assessed using percentage of agreement and Cohen's kappa (κ)

150   statistic, [25] with κ scores interpreted as fair (κ=0.21–0.40), moderate (κ=0.41–0.60), substantial

151 (κ=0.61–0.80) and almost perfect (κ=0.81–1.00).[26] Data were summarised using frequencies and

152 percentages for categorical variables and mean and standard deviation (SD) or median and lower

153 (Q1) and upper (Q3) quartiles for continuous variables. A hierarchical linear model was used to

154 investigate the relationship between motor vehicle and infrastructure characteristics and passing

155 distance. Characteristics were modelled as fixed effects. A random intercept and random slope were

156 applied for each rider, with each trip nested within the rider. The correlation type assumed was

157 AR(1), meaning that successive passing distances within the same trip were assumed to be

158 correlated. The hierarchical linear modelling was performed by a statistician (author: J.O.), who was

159 blinded to all variables with the exception of speed zone. As the presence of a marked on-road

160 bicycle lane and the presence of parked cars were highly related, these two variables were modelled

161 as an interaction. To evaluate the addition of other interaction terms, we ran fixed effects models

162 using maximum likelihood to compare various levels of interaction terms (saturated model, 3-way,

163 2-way and no interaction). Akaike and Bayesian information criterions demonstrated our chosen

164 model fitted the data the best while the likelihood ratio test also preferred this model after adjusting

165 for multiple testing. Speed zone was missing in 7.3% (n=1350) of passing events and vehicle type was

166 missing in 0.01% (n=23) of passing events and these events were excluded from the hierarchical

167 linear model. Additional hierarchical linear models were used to quantify the average distance

168 participants travelled per trip, the average number of passing events per 10 km travelled and the

169 average number of passing events less than 100cm per 10 km travelled. Data are reported as

170 averages with 95% confidence intervals (CI).

171 Two sensitivity analyses were conducted. Firstly, the impact of excluding cases with missing speed

172 zone (n=1350) was evaluated. A chi-square goodness of fit test was used to compare the average

173 passing distance when the model included and excluded speed zone (observations with missing

174 speed zone were excluded from both models). Secondly, we investigated the relationship between

175 motor vehicle and infrastructure characteristics and passing distance relative to legislated passing

176 distances in other regions of Australia. Legalisation or trials of minimum passing distances have been

177   legislated in other regions of Australia and stipulate that drivers must provide a passing distance of

178   at least 1 metre when the speed limit is 60 km/h or less, and 1.5 metres when the speed limit is

179   more than 60 km/h.[27] Therefore, in this sensitivity analysis, we centred passing distance at 1 metre

180   in speed zones of 60 km/h or less and 1.5 metres in speed zones of greater than 60 km/h. Negative

181   and positive values of passing distance were therefore relative to these recommended passing

182   distances. A chi-square goodness of fit test was used to compare this model with the main model

183   with passing distance as an absolute value.

184   Data analysis was performed using Stata (Version 14.2, StataCorp, College Station, TX) and SAS

185   (Version 9.4, SAS Institute Inc., Cary, NC, USA). The importance of a variable was assessed by its p-

186   value and effect size.

187

188   **RESULTS**

189   Sixty-three participants consented to participate. Of these, complete data were available for 60

190   participants (two participants were not able to activate the device and one participant did not ride

191   during the data collection period). The participants with complete data had a median age of 39.3

192   years (Q1: 32.0 years, Q3: 48.5 years) and 75% (n=45) were male. A total of 422 trips were recorded,

193   with a mean of 7 trips per participant (SD: 3.14). Participants rode a total of 5,302 km, of which

194   4,831 km (91%) was classified as on-road. The average trip distance was 12.6 km (95% CI: 11.9, 13.3)

195   of which the average distance ridden on-road per trip was 11.5 km (95% CI: 10.9, 12.1).

196   A total of 18,527 passing events were recorded with a median passing distance of 173 cm (Q1:

197   137cm, Q3: 224cm; range: 24cm – 330cm). Participants recorded an average of 28.0 passing events

198   per 10 km travelled (95% CI: 25.8, 30.4). Of these, 0.7% were less than 60cm, 1.4% between 60 and

199   79cm and 3.8% between 80 and 99cm (Table 1). Overall, 1,085 (5.9%) passing events were less than

200   100cm. Participants recorded an average of 1.7 passing events less than 100cm per 10 km travelled

201 (95% CI: 1.5, 1.9). For passing events in speed zones of 60 km/h or less (n=16,274; 95%), the

202 proportion of passing events less than 100cm was 5.9% (n=952). For passing events in speed zones

203 of greater than 60 km/h (n=903; 5%), the proportion of passing events less than 150cm was 32%

204 (n=293). Between-subject variation was noted for mean passing distances and for the proportion of

205 passing events less than 100cm. Mean passing distances varied between cyclists from 147cm to

206 230cm (Figure 2). The mean proportion of passing events less than 100cm varied between cyclists

207 from 0.9% to 29.9% (Figure 3).

208 Most passing events involved sedans (70.4%) or 4WDs (17.2%), occurred mid-block (89.8%),

209 occurred in the absence of a marked on-road bicycle lane (57.6%), in the absence of parked cars on

210 the kerbside (83.0%) and in speed zones of 50 km/h (22.6%) or 60 km/h (61.0%) (Table 1). Figures 5-

211 8 provide unadjusted differences in passing distances for each characteristic. The proportion of

212 passing events <100cm was greater when the cyclist was riding in a marked on-road bicycle lane

213 relative to a road without a bike lane (6.8% vs 5.1%; P<0.001).

214 Results from the hierarchical linear model are shown in Table 2. Relative to sedans, 4WDs had a

215 mean lower passing distance of 15cm (Q1: 12cm, Q3: 17cm) and buses had a reduced mean passing

216 distance of 28cm (Q1: 16cm, Q3: 40cm). Relative to passing events that occurred on roads without a

217 marked bicycle lane and without parked cars, passing events on roads with a bike lane with no

218 parked cars had a reduced mean passing distance of 27cm (Q1: 25cm, Q3: 29cm), and passing events

219 on roads with a bike lane and parked cars had a reduced mean passing distance of 40cm (Q1: 37cm,

220 Q3: 43cm) (Figure 9). Passing events that occurred on roads without a marked bicycle lane and

221 without parked cars had a lower estimated proportion of passing events <100cm (5%) compared to

222 passing events that occurred on roads with a bike lane and parked cars (9%). There were no notable

223 differences between locations or speed zones.

224 **Sensitivity analyses**

225 In a sensitivity analysis comparing the primary model with a model that included all variables with

226 the exception of speed zone (and included all cases), there were no significant differences in model

227 coefficients (χ^2=1.302; df=12; P>0.99). Similarly, in a sensitivity analysis comparing the primary

228 model with a model with passing distance centred around 1 metre in speed zones of 60 km/h or less

229 and 1.5 metres in speed zones of greater than 60 km/h, there were no significant differences in

230 model coefficients (χ^2=0.046; df=18; P>0.99).

231 **Inter-rater reliability**

232 There were 558 passing events that were independently coded by two coders. 513 (92%) were

233 coded by both coders and 45 (8%) were coded by only one coder. There was almost perfect

234 agreement for location (κ = 0.88; 95% CI: 0.82, 0.94), bike lane (κ = 0.82; 95% CI: 0.77, 0.87) and the

235 presence of parked cars (κ = 0.84; 95% CI: 0.77, 0.90), and substantial agreement for vehicle type (κ

236 = 0.69; 95% CI: 0.62, 0.76). The most frequent disagreement for vehicle type was sedan and 4WD

237 (percentage agreement = 42%).

238

239 **DISCUSSION**

240 We quantified the distance that motor vehicles provide when passing cyclists and investigated the

241 impact of motor vehicle and road infrastructure characteristics on passing distance. In a sample of

242 18,527 passing events, approximately one in every 17 passing events was a 'close' pass (<100cm). In

243 higher speed zones, over 60kph, one in every three passing events was a 'close' pass (<150m). We

244 noted important links between motor vehicle types and infrastructure characteristics, and passing

245 distance. These data demonstrate that road infrastructure is associated with passing distance and

246 can be used to inform the selection and design of cycling-related infrastructure.

247 Previous studies that have quantified the passing distance that motor vehicles provide to cyclists

248 have commonly used an instrumented bicycle on a set route,[10-13] or have used a limited number of

249   fixed traffic cameras to estimate passing distance.[15] To our knowledge, our study is the first study to

250   use technology mounted on cyclists' own bicycles to quantify passing distance with cyclists riding on

251   self-selected routes. Furthermore, the number of passing events in our study (n=18,527) is

252   substantially larger than that previously reported (e.g. n=145,[11] n=1380,[12] n=1846[15]; see Table 3). In

253   the current study, we observed a mean passing distance of 173cm. This is slightly lower than data

254   from another Australian state, Queensland, in which a mean passing distance of 186cm was

255   reported,[15] and 6.4 ft (195cm) reported in Wisconsin, United States.[13] In contrast to our study, both

256   of these prior studies were conducted in settings with legislated bicycle passing distance rules.

257   Data on the effectiveness of marked on-road bicycle lanes in reducing crashes are limited. Some

258   studies have suggested that bicycle lanes offer reduced crash risk,[28-30] while others have suggested

259   that they offer no benefit.[31] The findings of the current study indicate that passing distance was

260   reduced when the cyclist was riding in a marked on-road bicycle lane, and this is supported by a

261   study from the United Kingdom that reported a reduced passing distance of between 7cm and

262   18cm.[10] In addition, we observed a greater rate of close passing events when the cyclist was riding

263   on a road with a marked bicycle lane (6.8% vs 5.1%). It has been suggested that this is a result of

264   driver perceptions. Specifically, in situations where the cyclist is in the same lane as the motorist, the

265   driver is required to perform an overtaking manoeuvre (i.e. change lanes to pass). Whereas, in

266   situations where the cyclist is in a dedicated marked bicycle lane, the motorist has a clear lane ahead

267   and is not required to perform an overtaking manoeuvre.[10] As a result, there is less of a conscious

268   requirement for drivers to provide additional passing distance.

269   Road lane width has also been identified as an important factor with increased lane widths having

270   been shown to facilitate greater passing distances.[18] Furthermore, lane widths may also explain

271   some of the variation in passing distance we observed between vehicle types. For example, the

272   reduced passing distance observed with buses, relative to sedans, may be explained by the greater

273   width of buses. We were unable to obtain accurate lane width data across the entire road network

274   of metropolitan Melbourne and thus this is a factor we were unable to control for. Similarly, the

275   number of lanes of traffic in the direction of travel for the cyclist may also influence driver

276   overtaking manoeuvres and hence passing distance. However, these data were also unavailable.

277   The reduction in passing distance when the cyclist was riding in a marked bicycle lane was further

278   exacerbated when parked cars were present. The reduced passing distance in the presence of

279   parked cars may be explained by cyclists' choice of lane position, in that they may be electing to

280   move outside of the 'dooring' zone.[32] It has also been shown that cyclist crash odds are higher on

281   roads with parked cars relative to roads without parked cars.[30] We noted substantial between-cyclist

282   variation in mean passing distances and the proportion of close passing events. This is suggestive of

283   an influence of rider behaviour or route selection on passing distance. However, further work is

284   required to quantify this.

285   We observed no notable differences in passing distances between speed zones, suggesting that

286   drivers do not adapt the clearance provided to cyclists with speed. In other regions of Australia (with

287   the exception of our region of Victoria), legalisation or trials of minimum passing distances have

288   been legislated and stipulate that drivers must provide a passing distance of at least 1 metre when

289   the speed limit is 60 km/h or less, and 1.5 metres when the speed limit is more than 60 km/h. In line

290   with our finding that passing distance did not differ between speed zones, and consistent with

291   Debnath *et al.* (2018),[15] we observed a higher proportion of passing events in which the passing

292   distance was less than these suggested boundaries in speed zones of greater than 60 km/h. Given

293   that passing vehicle speed is known to be a major concern for cyclists,[33] speed-based minimum

294   passing distance regulations are justified, and our results demonstrate the need to increase

295   education for drivers to provide greater passing distance at higher vehicle speeds.

296   Overall, these findings have important implications for the selection and design of cycling-related

297   infrastructure. Specifically, these findings suggest that marked on-road bicycle lanes, particularly

298   alongside parked cars, are not the optimal solution for maximising motor vehicle passing distance.

299   This begs the question: is a single stripe of white paint enough to protect cyclists? That is not to

300   suggest that we should not provide on-road marked bicycle lanes. Rather, the focus of on-road

301   cycling infrastructure needs to be on providing infrastructure that separates cyclists from motor

302   vehicles by a physical barrier. If this is not possible, then at a minimum, buffer zones should be

303   provided between the edge of the cycle lane and motor vehicle traffic lanes, and, if necessary,

304   between the bicycle lane and parked cars.

305   The proportion of close passing events recorded in this study reflects one close passing event for

306   every 17 motor vehicles that pass. Given that close passing events are a key contributor to reduced

307   perceived safety in cyclists,[7] it is clear that efforts to reduce close passing events will improve the

308   experience of people cycling on our roads with the aim of increasing cycling participation.

309   The strengths of this study include the use of on-bike technology that enabled the quantification of

310   passing distance while cyclists were using their own bicycles and as part of normal riding. The

311   manual review of all recorded events, while time-consuming, provided a robust and detailed

312   approach to classifying motor vehicle and road infrastructure characteristics, and for confirming

313   motor vehicle passing events (and excluding situations in which a cyclist undertook a motor vehicle).

314   Although some variation was noted between coders. Furthermore, data were collected on cyclists

315   riding in metropolitan Melbourne and therefore these data may not be reflective of cyclists in outer

316   suburbs or regional areas. Additionally, given the frequency of data collection from the ultrasound

317   sensor, it is likely that the sensor detected the motor vehicle body, rather than the side mirrors, and

318   therefore passing distances are likely to be conservative estimates. Additionally, the proportion of

319   passing events less than 100cm is related to the maximal distance that the sensor can read. For

320   example, if the maximal recordable distance is restricted to 300cm, 250cm or 200cm, the proportion

321   of close passing events increases to 6.1%, 7.0% and 8.9%, respectively. A small amount of data were

322   missing for speed zone, which was an artefact of lost GPS signals. However, sensitivity analyses

323   revealed that this did not appreciably impact on model estimates. Further, and as noted above, data

324   were not available on road lane widths, bicycle lane widths or number of lanes and hence we could

325   not control for these factors. Additionally, there were a small number of passing events that could

326   not be coded due to inadequate ambient lighting and these events were excluded from analyses.

327   There is also a need to understand how cyclists' subjective experiences align with quantified passing

328   distances.

329

330   **CONCLUSION**

331   From a large sample of events in which a motor vehicle passed a cyclist, one in every 17 passing

332   events was a close passing event (<100cm) and in higher speed zones (over 60kph), one in every

333   three was a close passing event (<150cm). We identified that road infrastructure had a substantial

334   influence on the distance that motor vehicles provide when passing cyclists. Specifically, we

335   demonstrated that on-road bicycle lanes reduced passing distance. These data can be used to inform

336   the selection and design of cycling-related infrastructure that actually provides a safety benefit for

337   cyclists.

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REFERENCES

1. Teschke K, Reynolds CC, Ries FJ, Gouge B, Winters M. Bicycling: Health risk or benefit. *UBC Medical Journal.* 2012;3(2):6-11.
2. Celis-Morales CA, Lyall DM, Welsh P, et al. Association between active commuting and incident cardiovascular disease, cancer, and mortality: prospective cohort study. *BMJ.* 2017;357(j1456).
3. Mueller N, Rojas-Rueda D, Cole-Hunter T, et al. Health impact assessment of active transportation: a systematic review. *Prev Med.* 2015;76:103-114.
4. Beck B, Cameron P, Fitzgerald MC, et al. Road safety: serious injuries remain a major unsolved problem. *Med J Aust.* 2017;207(6):244-249.
5. Beck B, Stevenson M, Newstead S, et al. Bicycling crash characteristics: An in-depth crash investigation study. *Accid Anal Prev.* 2016;96:219-227.
6. Heesch KC, Sahlqvist S, Garrard J. Gender differences in recreational and transport cycling: a cross-sectional mixed-methods comparison of cycling patterns, motivators, and constraints. *International Journal of Behavioral Nutrition and Physical Activity.* 2012;9(1):106.
7. Heesch KC, Sahlqvist S, Garrard J. Cyclists' experiences of harassment from motorists: Findings from a survey of cyclists in Queensland, Australia. *Prev Med.* 2011;53(6):417-420.
8. Chataway ES, Kaplan S, Nielsen TAS, Prato CG. Safety perceptions and reported behavior related to cycling in mixed traffic: A comparison between Brisbane and Copenhagen. *Transportation Research Part F: Traffic Psychology and Behaviour.* 2014;23:32-43.
9. Foundation CPFatNH. Riding a Bike for Transport: 2011 Survey Findings. 2011; https://www.heartfoundation.org.au/images/uploads/publications/Cycling-Survey-2011-Riding-a-Bike-for-Transport.pdf. Accessed 13/11/2018.
10. Parkin J, Meyers C. The effect of cycle lanes on the proximity between motor traffic and cycle traffic. *Accid Anal Prev.* 2010;42(1):159-165.
11. Dozza M, Schindler R, Bianchi-Piccinini G, Karlsson J. How do drivers overtake cyclists? *Accid Anal Prev.* 2016;88:29-36.
12. Chuang K-H, Hsu C-C, Lai C-H, Doong J-L, Jeng M-C. The use of a quasi-naturalistic riding method to investigate bicyclists' behaviors when motorists pass. *Accid Anal Prev.* 2013;56:32-41.
13. Chapman J, Noyce D. Observations of driver behavior during overtaking of bicycles on rural roads. *Transportation Research Record: Journal of the Transportation Research Board.* 2012(2321):38-45.
14. Walker I. Drivers overtaking bicyclists: Objective data on the effects of riding position, helmet use, vehicle type and apparent gender. *Accid Anal Prev.* 2007;39(2):417-425.
15. Debnath AK, Haworth N, Schramm A, Heesch KC, Somoray K. Factors influencing noncompliance with bicycle passing distance laws. *Accid Anal Prev.* 2018;115:137-142.
16. Kovaceva J, Nero G, Bärgman J, Dozza M. Drivers overtaking cyclists in the real-world: Evidence from a naturalistic driving study. *Safety Science.* 2018.
17. Feng F, Bao S, Hampshire RC, Delp M. Drivers overtaking bicyclists—An examination using naturalistic driving data. *Accid Anal Prev.* 2018;115:98-109.
18. Love DC, Breaud A, Burns S, Margulies J, Romano M, Lawrence R. Is the three-foot bicycle passing law working in Baltimore, Maryland? *Accid Anal Prev.* 2012;48:451-456.
19. Walker I, Garrard I, Jowitt F. The influence of a bicycle commuter's appearance on drivers' overtaking proximities: an on-road test of bicyclist stereotypes, high-visibility clothing and safety aids in the United Kingdom. *Accid Anal Prev.* 2014;64:69-77.
20. Schramm AJ, Haworth NL, Heesch K, Watson A, Debnath AK. *Evaluation of the Queensland minimum passing distance road rule.* Brisbane, Australia: Queensland University of Technology;2016.
21. Austroads. *Cycling Aspects of Austroads Guides.* Sydney, NSW, Australia: Austroads;2017.

403 22. Kempinska K, Davies T, Shawe-Taylor J, Longley P. Probabilistic Map-Matching for Low-
404   Frequency GPS Trajectories. Paper presented at: Proceedings of GIS Ostrava2017.
405 23. Kempinska K, Davies T, Shawe-Taylor J. Probabilistic map-matching using particle filters.
406   *arXiv preprint arXiv:161109706.* 2016.
407 24. VicRoads. Speed Zone Data. 2017; https://www.data.vic.gov.au/data/dataset/speed-zone-
408   data. Accessed 01 October 2017.
409 25. Viera AJ, Garrett JM. Understanding interobserver agreement: the kappa statistic. *Fam Med.*
410   2005;37(5):360-363.
411 26. Landis JR, Koch GG. The measurement of observer agreement for categorical data.
412   *Biometrics.* 1977:159-174.
413 27. Amy Gillet Foundation. Amy Gillet Foundaton: A Metre Matters. 2018;
414   http://www.amygillett.org.au/programs-resources/a-metre-matters. Accessed 06 Feburary
415   2018.
416 28. Reynolds C, Harris MA, Teschke K, Cripton PA, Winters M. The impact of transportation
417   infrastructure on bicycling injuries and crashes: a review of the literature. *Environmental*
418   *Health.* 2009;8(1):47.
419 29. Teschke K, Frendo T, Shen H, et al. Bicycling crash circumstances vary by route type: a cross-
420   sectional analysis. *BMC Public Health.* 2014;14(1):1.
421 30. Teschke K, Harris MA, Reynolds CC, et al. Route infrastructure and the risk of injuries to
422   bicyclists: a case-crossover study. *Am J Public Health.* 2012;102(12):2336-2343.
423 31. Mulvaney C, Smith S, Watson M, et al. Cycling infrastructure for reducing cycling injuries in
424   cyclists. *Cochrane Database of Systematic Reviews 2015.* 2015;12.
425 32. Hatfield J, Poulos RG, Rissel C, et al. Factors associated with cyclists' self-reported choice of
426   lane position. *Transportation Research Part F: Traffic Psychology and Behaviour.*
427   2018;55:403-414.
428 33. Fishman E, Washington S, Haworth N. Barriers and facilitators to public bicycle scheme use:
429   A qualitative approach. *Transportation Research Part F: Traffic Psychology and Behaviour.*
430   2012;15(6):686-698.
431 34. Llorca C, Angel-Domenech A, Agustin-Gomez F, Garcia A. Motor vehicles overtaking cyclists
432   on two-lane rural roads: Analysis on speed and lateral clearance. *Safety Science.*
433   2017;92:302-310.

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438 *Table 1: Number of passing events by passing distance, motor vehicle or infrastructure characteristic.*

Characteristic		N (%)	Passing distance Mean (SD)
Passing distance			
	0-59 cm	124 (0.7%)	
	60-79 cm	254 (1.4%)	
	80-99 cm	707 (3.8%)	
	100-119 cm	1528 (8.2%)	
	120-149 cm	3652 (19.7%)	
	150-199 cm	5861 (31.6%)	
	200-249 cm	3305 (17.8%)	
	250 cm and greater	3096 (16.7%)	
Motor vehicle type			
	Sedan	13031 (70.4%)	185 (61)
	Taxi	357 (1.9%)	166 (60)
	4WD	3173 (17.1%)	177 (59)
	Truck	379 (2.0%)	185 (69)
	Bus	86 (0.5%)	161 (71)
	Other	1478 (8.0%)	176 (60)
Location			
	Intersection related	1884 (10.2%)	182 (65)
	Mid-block	16631 (89.8%)	183 (60)
	Roundabout	12 (0.1%)	167 (84)
Presence of a marked on-road bicycle lane			
	No	10674 (57.6%)	196 (65)
	Yes	7853 (42.4%)	164 (49)
Presence of parked cars on the kerbside			
	No	15381 (83.0%)	188 (62)
	Yes	3146 (17.0%)	158 (49)
Speed zone[a]			
	40 km/h or less	1931 (11.2%)	168 (56)
	50 km/h	3873 (22.5%)	170 (57)
	60 km/h	10470 (61.0%)	190 (62)
	70 km/h	345 (2.0%)	189 (62)
	80 km/h	539 (3.1%)	182 (58)
	100 km/h	19 (0.1%)	154 (51)

439   Note: Missing data: a) n=1,350 (7.3%)

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Table 2: Results of the hierarchical linear model investigating the relationship between motor vehicle and infrastructure characteristics, and passing distance (N=17,156). Values represent the difference of least square means.

Characteristic		Difference in passing distance (Q1, Q3) (cm)
Motor vehicle type		
	Sedan	*Reference*
	Taxi	- 8 (-14, -2)
	4WD	-15 (-17, -12)
	Truck	-8 (-14, -2)
	Bus	-28 (-40, -16)
	Other	-12 (-15, -9)
Location		
	Intersection related	*Reference*
	Mid-block	9 (6, 11)
Interaction of bicycle lane and parked cars		
	No bike lane, no parked cars	*Reference*
	Bike lane, no parked cars	-27 (-29, -25)
	No bike lane + parked cars	-30 (-34, -27)
	Bike lane + parked cars	-40 (-43, -37)
Speed zone		
	40 km/h or less	-8 (-11, -5)
	50 km/h	-5 (-8, -3)
	60 km/h	*Reference*
	70 km/h	-7 (-14, -1)
	80 km/h	-6 (-12, 0)
	100 km/h	-18 (-43, 7)

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Table 3: Summary of prior studies that quantified the lateral passing distance that motor vehicles provide when passing cyclists.

Study	Number of passing events	Number of riders	Number of trips	Details
Current study	18,527	60	422	Device installed on cyclist's own bicycle
Other studies				
Walker *et al.* (2014)[19]	5,690	1	67	Instrumented bicycle
Feng *et al.* (2018)[17]	4,789	Unknown	Unknown	Existing motor vehicle naturalistic driving study
Llorca *et al.* (2017)[34]	2,928	1	7	Instrumented bicycle
Walker (2007)[14]	2,355	1	Unknown	Instrumented bicycle
Debnath *et al.* (2018)[15]	1,846	Unknown	Unknown	Video observations at 15 sites
Chuang *et al.* (2013)[12]	1,380	34	34	Instrumented bicycle
Chapman & Noyce (2012)[13]	1,151	Unknown	Unknown	Instrumented bicycle
Parkin & Meyers (2010)[10]	843	Unknown	Unknown	Instrumented bicycle
Love *et al.* (2012)[18]	586	5	34	Video camera mounted on cyclists' own bicycle
Dozza *et al.* (2016)[11]	145	2	Unknown	Instrumented bicycle
Kovaceva *et al.* (2018)[16]	83	Unknown	Unknown	Existing motor vehicle naturalistic driving study

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FIGURES

A

B

Figure 1: The MetreBox device (A) and the device installed on a bicycle with GoPro camera mounted on handlebars (B).

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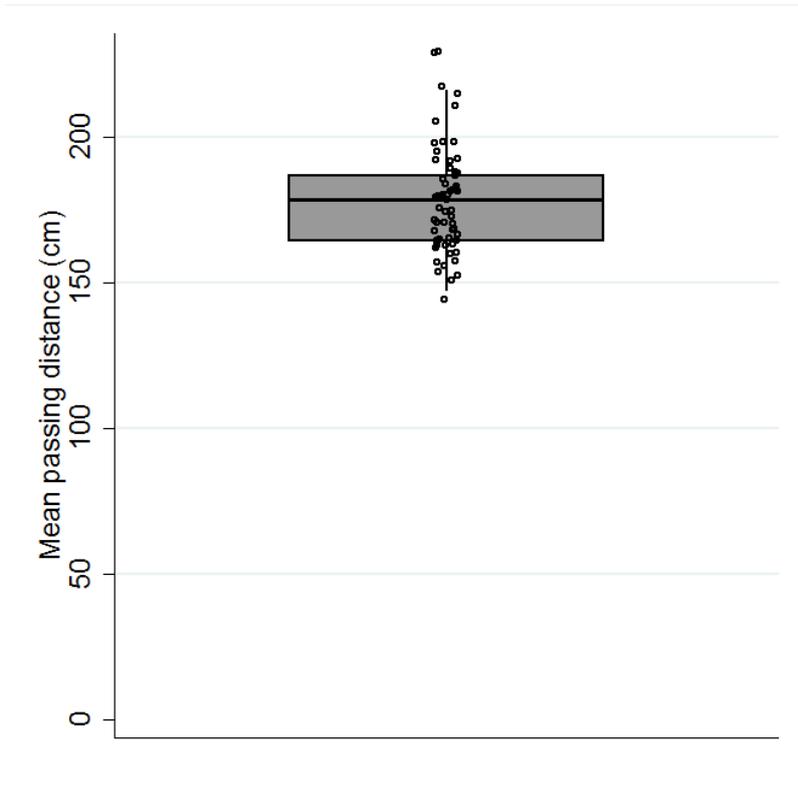
455

456   *Figure 2: Mean passing distance per participant (markers reflect individual participants).*

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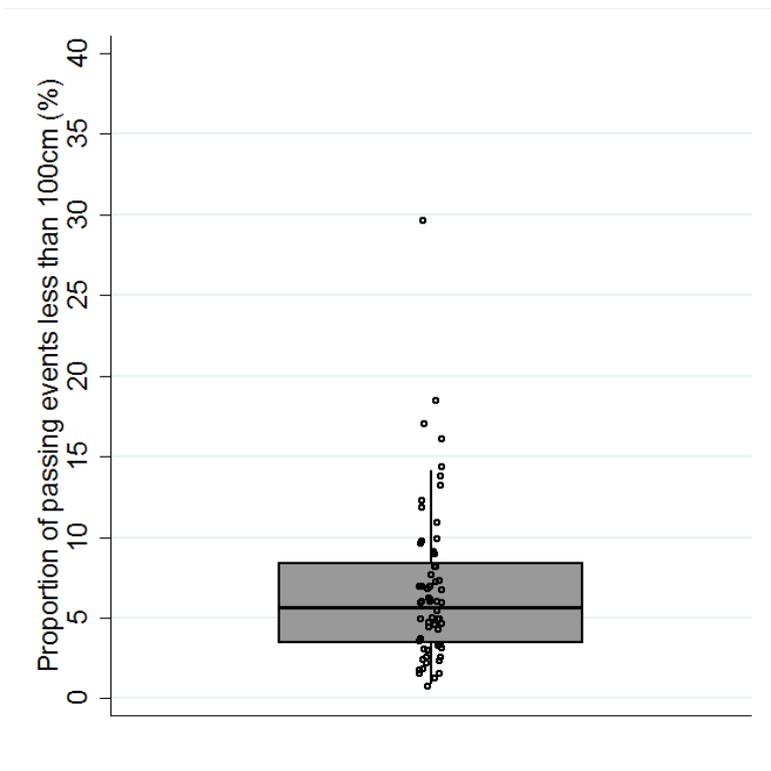
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459   *Figure 3: Mean proportion of passing events less than 100cm per participant (markers reflect individual participants).*

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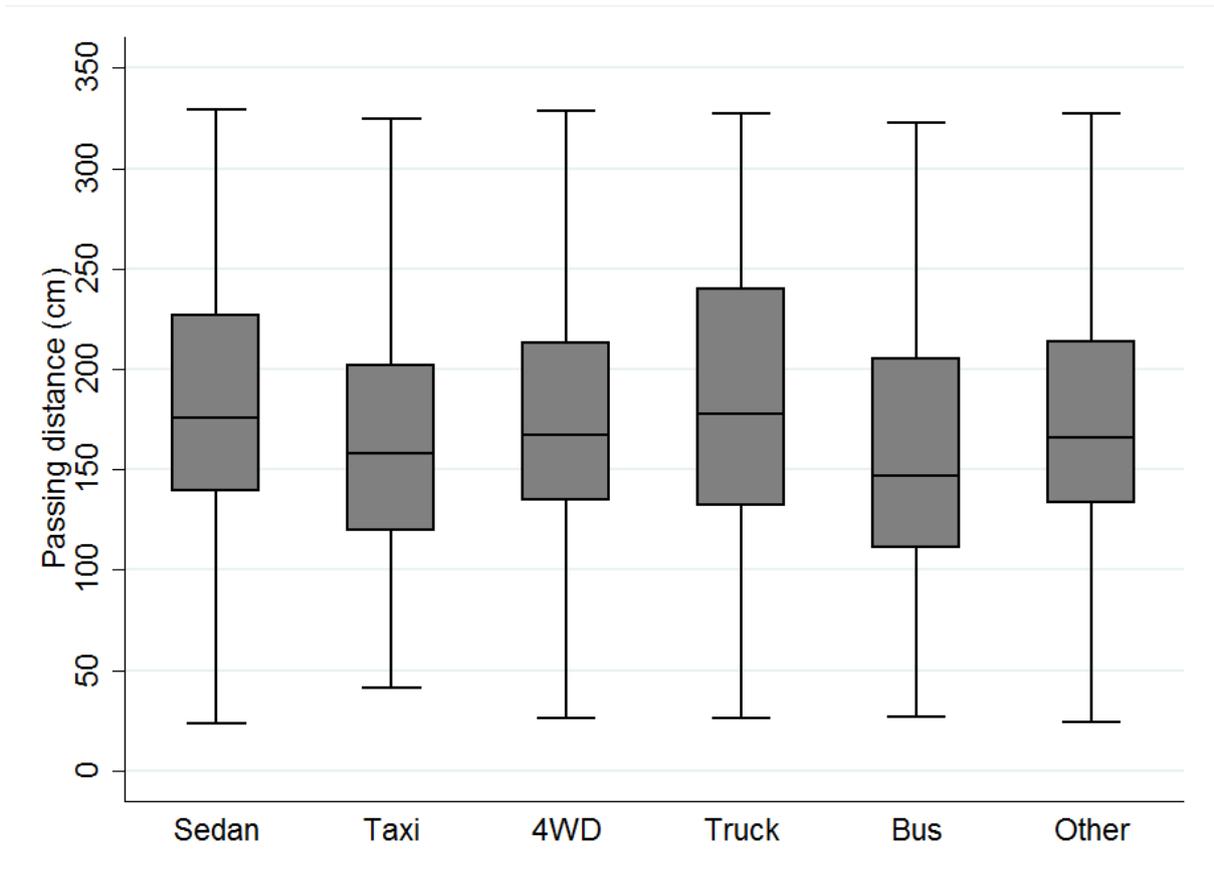
Figure 4: Mean passing distance by motor vehicle type.

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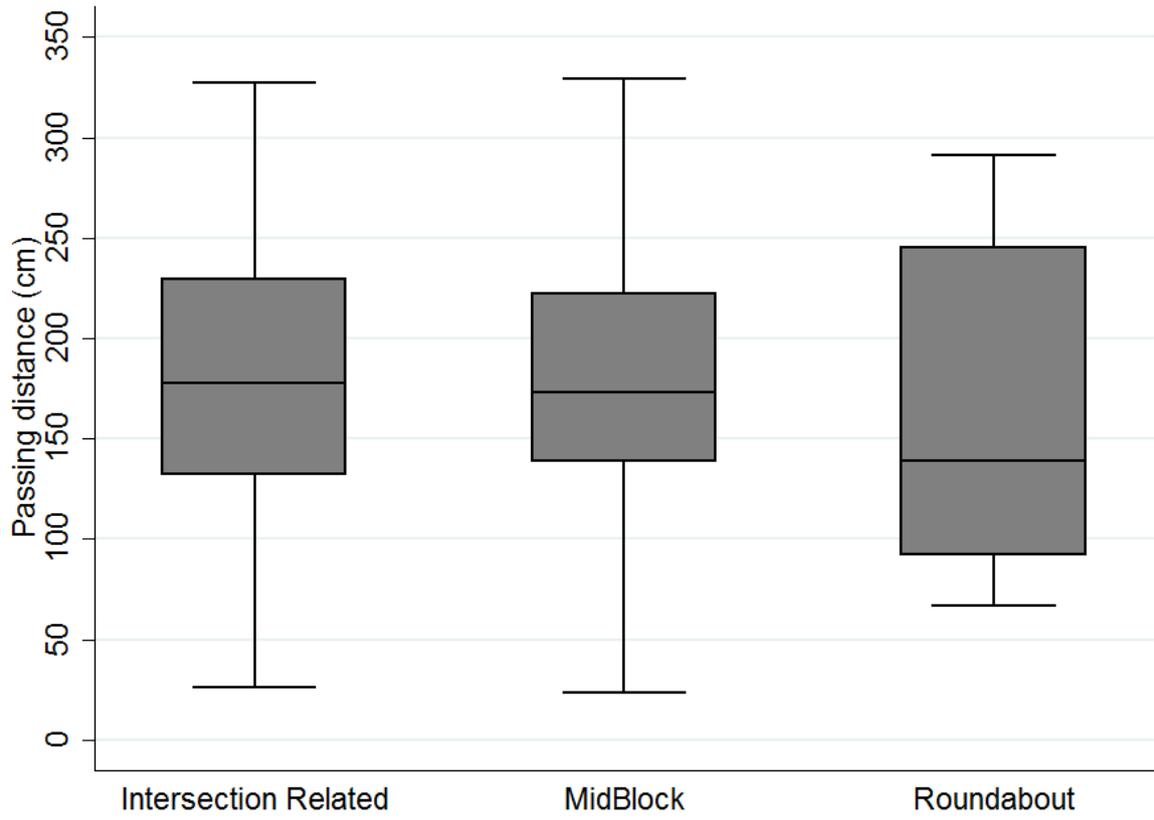
464

465   *Figure 5: Mean passing distance by location.*

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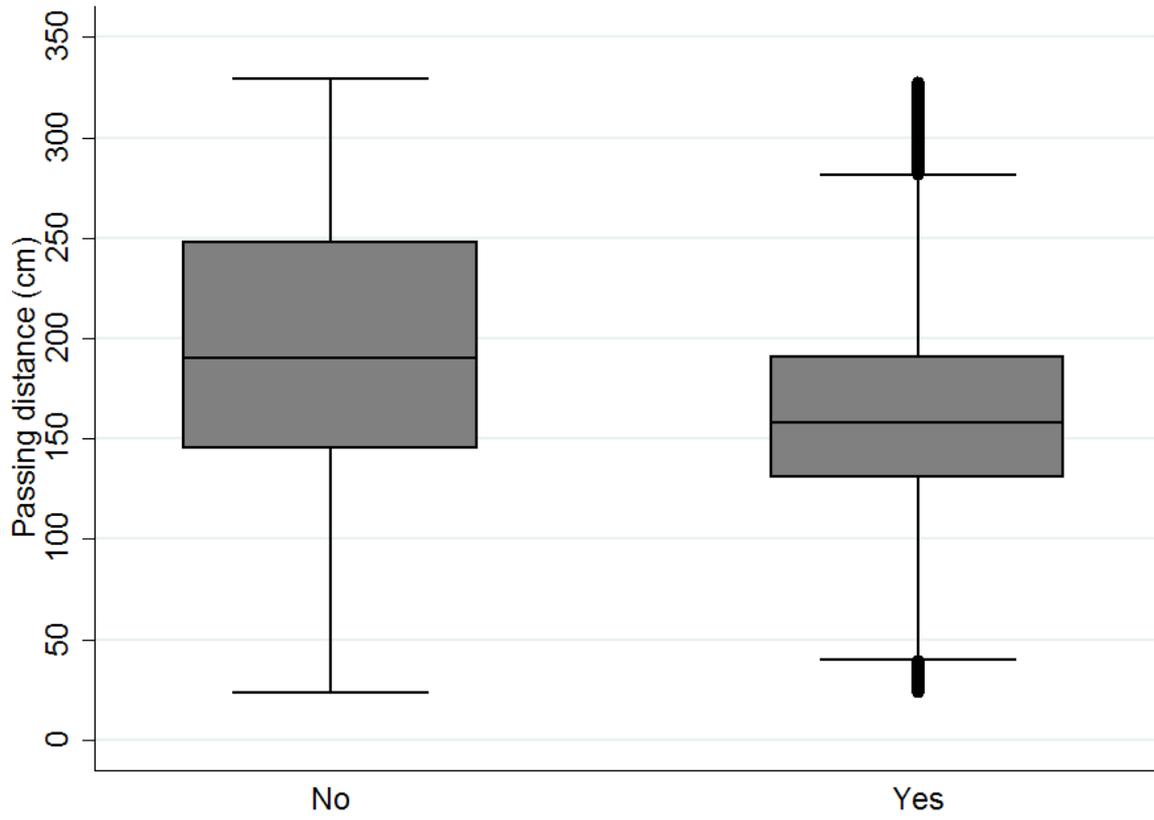
467

468   *Figure 6: Mean passing distance by presence/absence of a marked on-road bicycle lane.*

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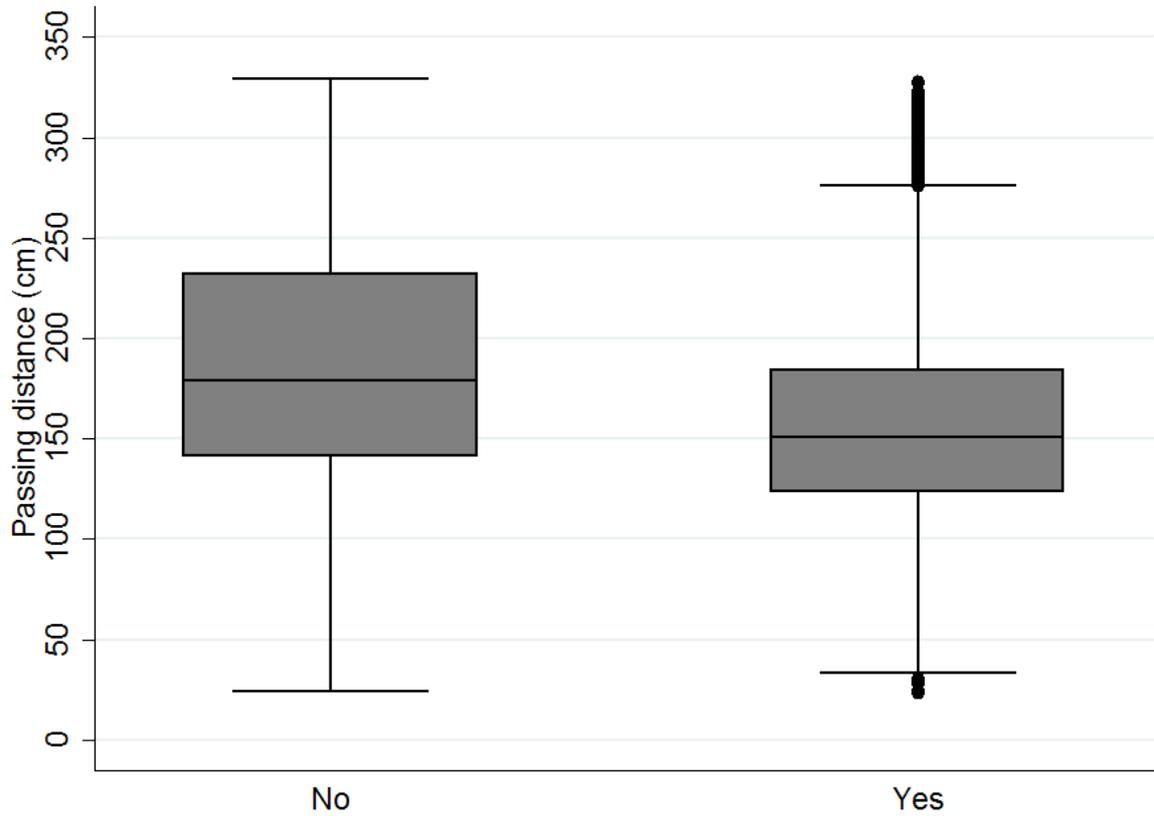
470

471   *Figure 7: Mean passing distance by the presence/absence of parked cars on the kerbside.*

472
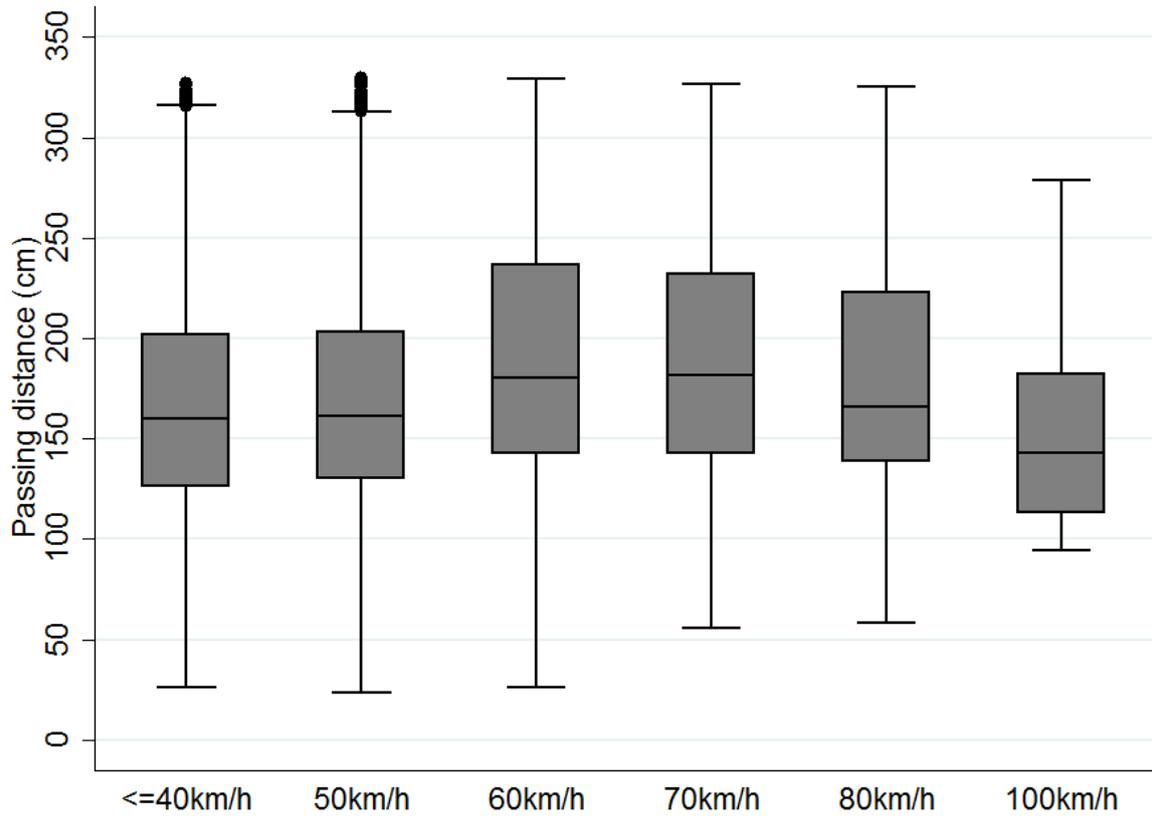
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474 *Figure 8: Mean passing distance by speed zone.*

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A: Reference

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B: 27cm less

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C: 30cm less

D: 40cm less

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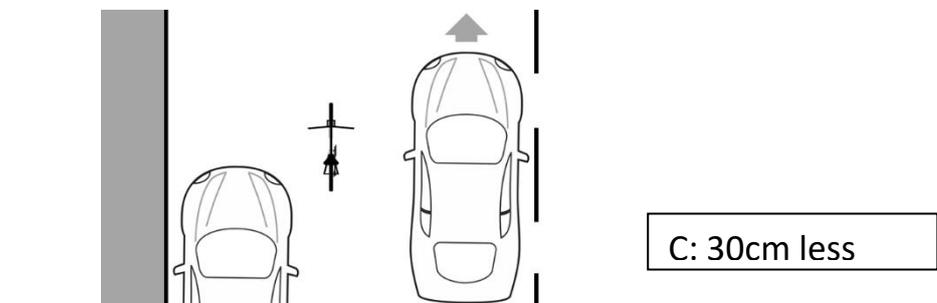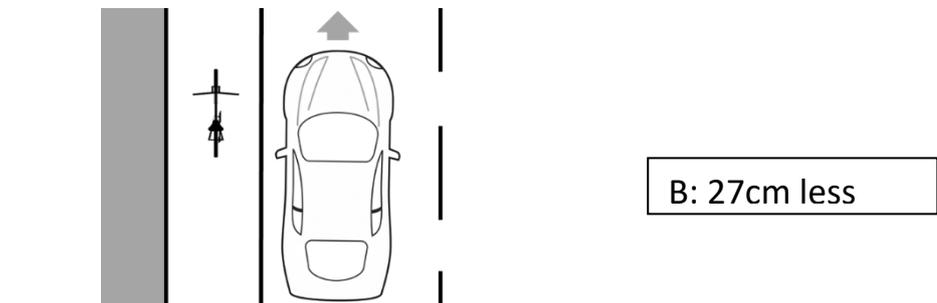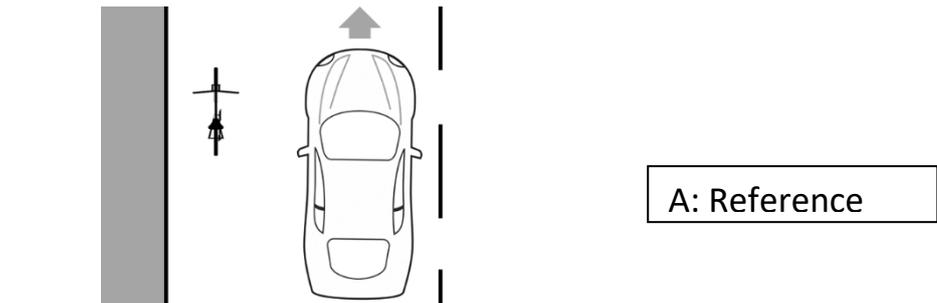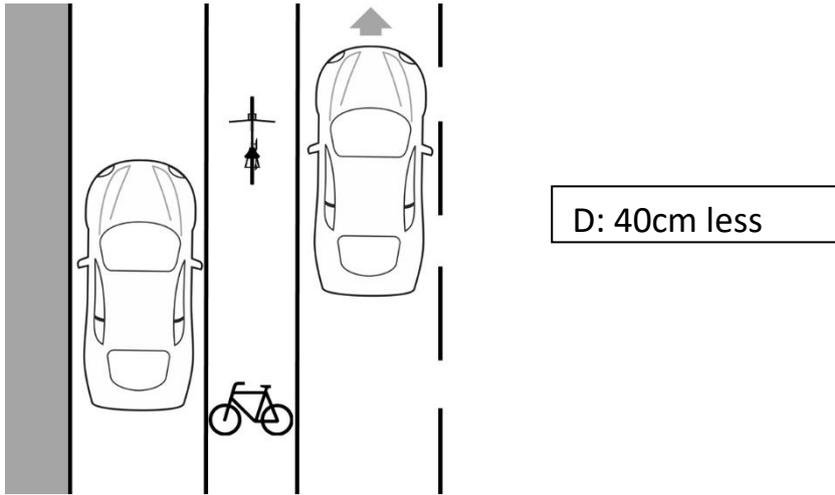
Figure 9: Results of hierarchical linear model for the interaction of bicycle lane and parked car on passing distance. Situation A reflects a scenario of no bike lane and no parked cars. Situation B reflects a scenario of a bike lane with no parked cars. Situation C reflects a scenario of no bike lane with parked cars. Situation D reflects a scenario of a bike lane with parked cars.