Moll Montaner, S.; López-Maldonado, G.; Rasch, A.; Dozza, M.; García García, A. (2021). Modelling duration of car-bicycles overtaking manoeuvres on two-lane rural roads using naturalistic data. Accident Analysis & Prevention. 160(106317):1-11. https://doi.org/10.1016/j.aap.2021.106317

Modelling duration of car-bicycles overtaking manoeuvres on two-lane rural roads using naturalistic data

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Abstract

Nowadays, Spanish two-lane rural roads frequently accommodate sport cyclists. They usually ride on the shoulder or on the right edge of the lane, sharing the infrastructure with motorised vehicles. Due to the speed difference between road users, the most frequent and dangerous interaction is in overtaking manoeuvres. One key factor from a safety and traffic operation point of view is the overtaking duration. The main aim of this paper is to analyse how factors related to the road, the cyclists, and the overtaking manoeuvre influence the duration of overtaking to cyclists on two-lane rural roads. Naturalistic field data were obtained using instrumented bicycles. Seven groups of cyclists, formed by different numbers of cyclists riding in-line and two-abreast, rode along five rural roads with different geometric and traffic characteristics. A total of 1592 flying manoeuvres, in which drivers did not reduce their speed, and 192 accelerative manoeuvres were analysed. The overtaking duration, considering each overtaking strategy, was modelled using Bayesian statistics. Results showed that flying manoeuvres were more prevalent than accelerative. They were performed with higher speeds and lower lateral clearances and, therefore, presented lower overtaking durations. For both overtaking strategies, duration increased on wider roads and with a larger size of the group. The presence of an oncoming vehicle decreased the overtaking duration. However, other factors presented opposite effects on the duration depending on the overtaking strategy. The developed predictive models allow obtaining overtaking durations varying road and cyclist grouping characteristics. Results can be used by road administration to manage and propose some specific countermeasures to integrate the cyclists in a safe and efficient way on two-lane rural roads.

Keywords: Cycling safety, Overtaking duration, Two-lane rural road, Instrumented bicycle, Bayesian modelling

1 Introduction

Although Spanish two-lane rural roads were designed primarily for motorised vehicles, the presence of sport cyclists is now common on them. In fact, cycling is the third most practised sport in Spain, with 74,768 federated cyclists in 2019 (Ministerio de Cultura y Deporte, 2020).

However, most of Spanish two-lane rural roads do not have a specific cycling infrastructure, as is common in other European countries. This fact implies that cyclists and motorised drivers have to share the road and closely interact. Even though the number of federated cyclists remains stable in the last three years, the number of fatal accidents involving cyclists on rural roads has not decreased, occurring around 50 fatal accidents per year (Dirección General de Tráfico, 2019). This fact highlights the need to investigate the interactions between cyclists and drivers on rural roads, in order to integrate bicycle traffic in a safe and functional way.

While in urban environment crossing scenarios account for most of the crashes between drivers and cyclists (Brown et al., 2021), due to the differences in terms of speed, volume, and protection system, the most frequent and dangerous interaction between cyclists and motorists on rural roads is the overtaking manoeuvre (Bella and Silvestri, 2017; Llorca et al., 2017). In Spain, the overtaking manoeuvre is regulated; in fact, cyclists have to ride on rural roads on the shoulder or on the right edge of the road (if the shoulder is impassable) and the minimum lateral distance to overtake them is 1.5 m (Ministerio del Interior, 2003). Previous research has explored the overtaking to cyclists with different aims, although most of these studies were focused on safety, analysing the minimum lateral clearance between the overtaking vehicle and the bicycle during the manoeuvre. Rubie et al. (2020) performed a complete systematic review of 42 published papers related to the influence of several factors on the lateral passing distance. The studies that analysed the lane width effect stated that wider lanes increased the lateral clearance (Llorca et al., 2017; Debnath et al., 2018; Feng et al., 2018; Chapman and Noyce, 2014; Bella and Silvestri, 2019; Mecheri et al., 2020). The effect of the shoulder width on the lateral clearance was not significant in the studies realised by Dozza et al. (2016) and Mecheri et al. (2021), while García et al. (2015) obtained higher lateral clearances when wider shoulders were present. The presence of on-road bicycle lane was also analysed. Some studies concluded a negative effect of bicycle lanes on lateral clearance (Beck et al., 2019; Debnath et al., 2018; Feng et al., 2018), while Bella and Silvestri (2019) obtained a higher lateral clearance when a bicycle lane was present. These contradictory results can be explained by Mackenzie et al. (2021), who concluded that when a bicycle lane was present, a higher lateral clearance was generally observed, but in the case of roads with high traffic volumes and higher speed limits, the effect was opposite. The effect of the horizontal alignment was also studied, comparing overtaking manoeuvres realised on tangents and on curves. Tangents presented higher lateral clearances than curves in three studies (Debnath et al., 2018; Llorca et al., 2017; Garcia et al., 2019), while a contrary conclusion was obtained by Bella and Silvestri (2017). Related to traffic factors, the presence of an oncoming vehicle was correlated with lower lateral clearance (Dozza et al., 2016; Llorca et al., 2017; Feng et al., 2018; Kovaceva et al., 2018; Bianchi Piccinini et al., 2018; Rasch et al., 2020a).

Dozza et al. (2016) analysed the overtaking manoeuvre from the driver's point of view, identifying four phases of the manoeuvre: approaching, steering away, passing and returning. As a conclusion to their study, although lateral clearance is a key safety indicator, they stated that overtaking is a long and complex process that has to be fully described and analysed considering not only lateral clearance, but also more performance measures. Some of the previous studies included other safety indicators, additionally to lateral clearance, as overtaking vehicle speed, overtaking strategy or cyclist risk perception of overtaking events. Llorca et al. (2017) identified aerodynamic forces, measured by combining lateral clearance and vehicle speed, as the variables most correlated with the risk of the cyclists overtaking manoeuvre. Rasch et al. (2020a) considered not only the lateral clearance when the vehicle was in parallel to the bicycle, but also the safety margins for all potential collisions, introducing all phases of the overtaking manoeuvre in the safety analysis.

Another key factor related to the overtaking manoeuvre to cyclists is the overtaking strategy. Dozza et al. (2016) defined three types of overtaking strategy regarding the overtaking to cyclists: the *flying* strategy, in which drivers overtake cyclists while keeping their speed relatively constant; the *accelerative* strategy, in which drivers slow down and follow the cyclist for some time before passing; and the *piggy backing* strategy, adopted by drivers who follow the lead driver, so that two or more cars in a row overtake the cyclists. Previous studies focused on the differences between the strategy in which the overtaking manoeuvres are performed. Most of them related accelerative manoeuvres with higher lateral clearances (Dozza et al., 2016; Bianchi Piccinini et al., 2018; Rasch et al., 2020a). Farah et al. (2019), on the contrary, obtained lower lateral clearances for accelerative manoeuvres. In these previous studies, the accelerative strategy was considered safer since lower overtaking vehicle speeds were registered, and drivers had better control of the interaction with the cyclist and a possible oncoming vehicle. Bianchi Piccinini et al. (2018) concluded that the combination of lower safety margins and higher mean speeds in flying manoeuvres seems to pose a risk for cyclists. Therefore, when cyclists ride on two-lane rural roads, the overtaking manoeuvre type has a very important role.

Even though the overtaking manoeuvre to cyclists has been analysed in depth in recent years, most of these studies considered only one cyclist riding individually. In Spain, the presence of groups of cyclists on rural roads is very common, as revealed by the number of federated cycling clubs, which was 3878 in 2019 (Ministerio de Cultura y Deporte, 2020). Spanish regulation allows cyclists to ride in a group following different configuration, *in-line* or at maximum *two-abreast*. The effect of different groups of cyclists was studied by García et al. (2019) and López et al. (2020), who considered a group formed by three and ten cyclists, respectively. They concluded that when cyclists rode two-abreast, the lateral clearance decreased. They also verified the conclusion of Llorca et al. (2017), indicating that the perceived risk of cyclists is related to a combination of lateral clearance and overtaking vehicle speed. López et al. (2020) stated that when cyclists rode two-abreast, a higher percentage of accelerative manoeuvres (19%) was observed compared to the in-line configuration (8%). They obtained higher overtaking vehicle speed and lower lateral clearance for flying manoeuvres, both for in-line and two-abreast configurations, confirming the dangerousness of this type of strategy.

The main studies related to the overtaking manoeuvre to cyclists on rural roads are focused on safety, being the lateral distance, the overtaking strategy and the overtaking vehicle speed the main variables analysed. However, cycle traffic, especially when they ride in groups, also influences traffic operation on rural roads, mainly due to the difficulty that sometimes can exist to overtake the cyclists, and the time spent following them. Moll et al. (2021) analysed the influence on the traffic operation of sports cyclists on a narrow rural road by using a traffic microsimulator. They concluded that the presence of sports cyclists reduced the average travel speed and increased the percent followers and the delay of motorised vehicles. They also stated that the overtaking duration to different cyclist groups is a key factor to introduce the overtaking manoeuvre to cyclists into a traffic microsimulator.

Previous studies have investigated safety margins during overtaking to cyclists, but none of them has studied the influence of different factors related to overtaking manoeuvre on overtaking duration. The decision to overtake in a two-lane rural road requires the driver to invade the opposing traffic lane, with high head-on accident risk with opposing vehicles (Vlahogianni, 2013). Asaithambi and Shravani (2017) stated that the overtaking duration can be considered as a road safety variable because this is a time during which extreme hazards are manifest. Therefore, the longer the overtaking vehicle stays in the opposite lane, the longer the exposure time to a frontal collision risk; however, a too-short duration of overtaking may involve a dangerous manoeuvre for cyclists. Chuang et al. (2013) stated that the time dimension (passing time) may be another important aspect that influences bicyclists' behaviours during passing events.

To the best the authors knowledge, the car-bicycle overtaking has not been modelled. Therefore, this study contributes to research as the first to model duration in such manoeuvres. On the other hand, Vlahogianni (2013) and Bella and Gilusano (2020) modelled the overtaking duration between four-wheeled vehicles and realised by motorcycles, respectively, using classical survival analysis. They developed hazard-based duration models to analyse the likelihood of an overtaking manoeuvre to end. However, the Bayesian approach to data analysis provides a powerful way to handle uncertainty in all observations, model parameters, and model structure using probability theory (Gelman et al., 2020). Bayesian methods have several advantages over frequentist approaches, such as the ability to derive probability statements for every quantity of interest or explicitly incorporate prior knowledge about parameters into the model (Bürkner, 2018). On the other hand, Bayesian methods come with challenges, the main ones being proper prior selection and the high computational demand for fitting models. In recent decades, however, the rapid increase of computing power and new algorithms have contributed to overcoming model-fitting challenges (Bürkner, 2017). Bayesian statistics estimate the full (joint) posterior distribution of the parameters, which is more informative than estimating a single point, as in classical frequentist statistics (Bürkner and Vuorre, 2019).

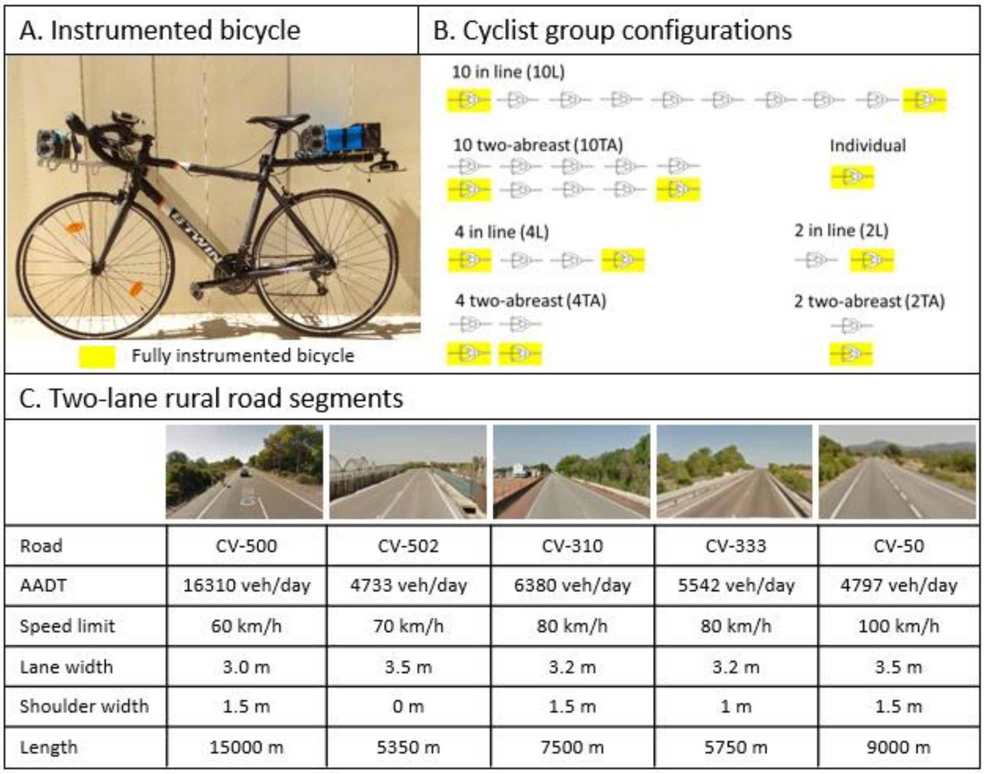
The main objective of this study was to obtain a predictive model of the duration of the overtaking manoeuvre between vehicles and bicycle groups considering different factors related to the road, the cyclist group, and the overtaking manoeuvre. Naturalistic data from overtaking events were collected using instrumented bicycles, and the overtaking duration and different factors were obtained from the field data processing. Taking into account the advantages, the overtaking duration was modelled using Bayesian statistics. Models considering different factors and response distributions were fitted and compared. Finally, the chosen models were validated, and the effects of each factor were analysed.

By using the developed predictive models, it is possible to obtain overtaking durations varying road characteristics and cyclists grouping configurations. These results can help road administration improve the safety and traffic operation on two-lane rural roads with bicycle traffic, modifying the infrastructure design or regulating the traffic conditions for both motorised and bicycle.

2 Methods

2.1 Data collection

A naturalistic data collection was carried out in Valencia using instrumented bicycles with different configurations of group of cyclists and on five different rural road segments. By using this method, it was possible to collect real data from overtaking manoeuvres with a high ecological validity. However, this method requires a large sample and considerable time and effort for data collection and processing (Chuang et al. 2013). Figure 1 shows the instrumented bicycle used (panel A), the configurations in which the group of cyclists rode (panel B) and the main characteristics of the road segments where the experiment was performed (panel C).



Road	CV-500	CV-502	CV-310	CV-333	CV-50
AADT	16310 veh/day	4733 veh/day	6380 veh/day	5542 veh/day	4797 veh/day
Speed limit	60 km/h	70 km/h	80 km/h	80 km/h	100 km/h
Lane width	3.0 m	3.5 m	3.2 m	3.2 m	3.5 m
Shoulder width	1.5 m	0 m	1.5 m	1 m	1.5 m
Length	15000 m	5350 m	7500 m	5750 m	9000 m

Figure 1. Data collection method.

2.2 Instrumented bicycles

The bicycles used to collect data were equipped with two small Garmin VIRB Elite video cameras with integrated GPS (1 Hz), which recorded HD videos with 30 frames per second. One camera was located at the rear of the bicycle, recording the approach of the overtaking vehicle and the initial phases of the overtaking manoeuvre. The second camera was located at the bicycle handlebar, recording the final phases of the manoeuvre and the oncoming traffic. The first and last bicycles of the group were also equipped with a laser device TruSense T200/T100 to collect the overtaking vehicle speed and the lateral clearance during the manoeuvre. The laser device was formed by two lasers located in the frontal and the rear part of the bicycles, and they were calibrated considering the distance between them. All this equipment was discreetly placed on the bicycles so as not to be detected by road users nor disturb cyclists (Figure 1.A).

2.3 Cyclist group configurations

Cyclist group configurations were designed based on previous observations on two-lane rural roads. Seven group configurations with different number of cyclists and in-line or two-abreast configurations were considered (Figure 1.B). The data collection, considering the groups of ten cyclists, was carried out on weekends, which is when the larger groups were observed on rural roads. The data collection considering the individual cyclist and the groups formed by two and four cyclists was performed on weekdays. In this way, the traffic demand registered during data collection takes into account the different traffic conditions registered on weekdays and on weekends.

Different cyclists participated in the experiment, who were changing their position within the group so that the results were not conditioned by the same cyclist. All the cyclists who took part in this experiment were semi-professionals and had experience riding on two-lane rural roads. They rode at the speed they considered as usual, so the study was more naturalistic. They wore sport clothes and bicycle helmet, since the helmet is mandatory in Spain.

2.4 Road segments

Data collection was carried out on five segments of two-lane rural roads. All of them have a high cycle demand and are part of common cycling routes. These road segments have different geometric and traffic (AADT) characteristics presented in Figure 1.C. AADT was obtained from data source of Provincial Council of Valencia (Diputació de València, 2020). The shoulders were paved and abutting the lane. The cyclists rode through these segments in the different group configurations considered in both travel directions.

2.5 Data reduction

A total of 24 data collection sessions were carried out. To obtain the study variables, data reduction and processing were required. In the field experiment, data from two sources were obtained: the cameras and the laser device. Garmin Virb Edit specific software was used to review the videos. Using this software, it was possible to synchronise the GPS data with each video to obtain the location of each manoeuvre and the speed of the bicycle. The review of the videos was performed manually, and the centre line type, the horizontal alignment, the invasion of the opposing lane, the lane and shoulder widths, the speed limit and the timeline of each overtaking manoeuvre were visually coded.

Once the videos from all the cameras were reviewed, the laser device data were processed and synchronised to complete the dataset. The laser device offered the relative speed of the overtaking vehicle when it was in parallel with the bicycles. The vehicle speed was obtained by adding the bicycle speed registered by the GPS to the relative speed. The lateral clearance is the minimum distance between the vehicle and the bicycles. It was obtained as the lateral distance registered by the laser device minus half the bicycle handlebar and minus the vehicle side mirror. To unify data of each manoeuvre, the most critical values of the records of the first and last bicycle in the group were chosen., i. e. the minimum lateral clearance, the maximum overtaking vehicle speed, and the higher opposing lane occupation.

2.6 Study variables

To obtain the overtaking duration to cyclists, it is essential to understand the development of the overtaking manoeuvre. The timeline of each overtaking manoeuvre was annotated considering the four phases defined by Dozza et al. (2016): 1) *approaching,* 2) *steering away,* 3) *passing,* and 4) *returning* (Figure 2).

Different times were registered during each overtaking manoeuvre:

- t_0 is the time when the vehicle arrives to the last bicycle of the group, and it is around 3 m behind the last bicycle.
- t_i is the time when the vehicle starts the overtaking manoeuvre in the steering away phase. It is noted as the time when the overtaking vehicle changes its trajectory or, in the case of flying overtaking without clearly visible trajectory change, it is the time when the overtaking vehicle arrives to the last bicycle of the group.
- t_p is the time when the vehicle is in parallel with the last bicycle of the group and starts the passing phase.
- t_p' is the time when the vehicle is in parallel with the first bicycle of the group and starts the returning phase.
- t_f is the time when the vehicle ends the overtaking manoeuvre and return to its natural position in the lane, ending the returning phase.
- t_{ov} is the time when each oncoming vehicle is first seen from the frontal camera of the first bicycle of the group.

The overtaking duration is defined as OD=t_f-t_i. It is the time in which the overtaking vehicle performs the passing manoeuvre due to the phases of steering away, passing and returning to its lane. The follow-up time recorded in accelerative manoeuvres corresponds to t_i-t_0, in that way, accelerative manoeuvres are defined when $t_0<t_i$. In flying manoeuvres, the overtaking starts when the vehicle arrives to the bicycles ($t_0=t_i$), or in some cases, even before reaching the bicycles ($t_0>t_i$). It is considered that an oncoming vehicle is present during the overtaking manoeuvre if $t_{ov} < t_i$,.

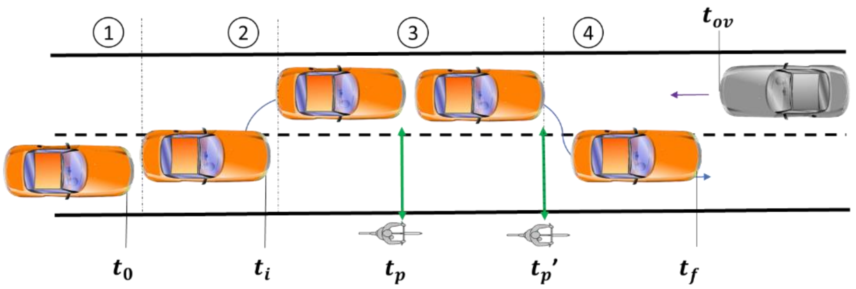


Figure 2. Timeline registered for each overtaking manoeuvre. t_0 is the time when the vehicle arrives to the last bicycle; t_i is the time when the vehicle starts the overtaking manoeuvre in the steering away phase; t_p and $t_{p'}$ are the times when the vehicle is in parallel with the last and first bicycles, respectively; t_f is the time when the vehicle ends the returning phase; t_{ov} is the time when the oncoming vehicle is first seen from the first bicycle.

The variables obtained from the field data collection used in this study were classified according to their relation to the road segment, the cyclist grouping and the overtaking manoeuvre. Table 1 shows the variables, the type and the code used to include them in the model.

Table 1. Variables registered in each overtaking manoeuvre.

Variable description	Variable Type	Variable Code
Related to the road segment		

Lane width (m)	Continuous	Lane
Shoulder width (m)	Continuous	Shoulder
Speed limit (km/h)	Continuous	Slimit
Annual Average Daily Traffic (veh/day)	Continuous	AADT
Related to the cyclists		
Number of cyclists in the group	Continuous	Cyclists
Configuration	Categorical	Conf
Related to the overtaking manoeuvre		
Overtaking strategy	Categorical	Ostrategy
Horizontal alignment	Categorical	Halign
Oncoming vehicle presence	Categorical	OncVis
Overtaking vehicle speed (km/h)	Continuous	Ovspeed
Lateral clearance (m)	Continuous	Clearance
Invasion of the opposing lane	Categorical	Invasion

2.7 Overtaking duration model

Bayesian regression models were used to model the overtaking duration considering different variables related to each manoeuvre. R Project's software and the brms package for Bayesian multilevel models, version 2.14.4, were used to fit the models. The brms package comes with many post-processing and visualization functions, including posterior predictive checks, leave-one-out cross-validation, visualization of estimated effects, and prediction of new data (Bürkner, 2017; Bürkner, 2018).

The overtaking duration (OD) data used in this study presented non-negative and uncensored values since only completed events were registered. The most used response distributions to model durations are Weibull and log-normal, as they are often considered for situations where a skewed distribution for a non-negative random variable is needed (Dumonceaux and Antle, 1973). In this study, exponential, Weibull and log-normal distributions, were used and compared in order to obtain the model that best fits the data.

The parameters of the log-normal distribution are the log-normal mean $\mu_{OD,i}$, that is the predictor, and the standard deviation of the log-normal distribution σ_{OD} which is assumed constant over all responses (Eq .1)

$$OD_i \sim Lognormal(\mu_{OD,i}, \sigma_{OD}) \tag{1}$$

The predictor contains the i-th row of the design matrix, $X_{OD,i}$, and the vector of population-level parameters β_{OD}:

$$\mu_{OD,i} = X_{OD,i}\,\beta_{OD} \tag{2}$$

Each row i of the design matrix contains the values of each population-level effect considered (factors showed in Table 1). Since different models with different population-level effects have been considered, the number of population-level effects F included in each model varies from 1 to k.

$$X_{OD,i} = [1\; X_{F1,i} \dots X_{Fk,i}] \tag{3}$$

The vector of parameters β_{OD} contains the parameters to be fitted for each population-level effect considered in each model. β_0 represents the intercept of the model, and β_{Fk} corresponds to the parameter to be fitted for each effect included in each model.

$$\beta_{OD} = [\beta_0\ \beta_{F1} \dots \beta_{Fk}]^T \tag{4}$$

For the Weibull and exponential response distributions, the predictor is transformed using a log link function and contains the same design matrix row and the vector of population-level parameters explained before.

Regarding the differences between the flying and the accelerative strategies highlighted in previous studies (Bianchi Piccinini et al., 2018; Rasch et al., 2020a; Farah et al., 2019), two sets of models, defined in Table 2 were fitted, one for flying manoeuvres and the other for accelerative ones.

Table 2. Models' design considering different variables and response distributions.

Factors	M1	M2	M3	M4	M5	M6	M7	M8
Lane	X	X	X	X	X	X	X	X
Shoulder	X	X	X	X	X	X	X	X
Slimit	X	X	X	X	X	X	X	X
AADT	X	X	X	X	X	X	X	X
Cyclists	X	X	X	X	X	X	X	X
Conf	X	X	X	X	X	X	X	X
Halign	X	X	X	X	X	X	X	X
OncVis	X	X	X	X	X	X	X	X
Ovspeed		X	X			X	X	X
Clearance				X	X	X	X	X
Resp. distr.	log-normal	Weibull	log-normal	Weibull	log-normal	Weibull	log-normal	exponential

In these models, different population-level effects were considered, and the response distribution was also varied. The overall goal was to determine 1) what factors best explain overtaking manoeuvres and 2) what distribution best fits these data. The invasion of the opposing lane was not considered, because it depends on the lateral clearance and the road width. Due to its high range of values, the AADT variable was standardised by subtracting the mean and dividing by the standard deviation.

The models were fitted using four chains, each with 2000 iterations, of which the first 1000 were warmup to calibrate the sampler and discarded, leading to a total of 4000 posterior samples. Weakly informative prior distributions of the parameters were used (Bürkner, 2017).

To evaluate the models and compare them, Bayesian leave-one-out cross-validation (LOOCV) was used (Vehtari et al., 2017). LOOCV gives a nearly unbiased estimate of the predictive ability of a given model and allows to compare different models applied to the same data. A higher estimate of the expected log predictive density (ELPD) indicates a better fit of the model (Vehtari et al., 2017).

Bayesian R^2 was conducted to measure the predictive performance of each model. Following the method described by Gelman et al. (2019), Bayesian R^2 is defined from a Bayesian point of view as the predicted variance divided by the predicted variance plus the error variance. Bayesian R^2 can be considered as a data-based estimate of the proportion of variance explained for new data. The selected models were further assessed with 10-fold cross-validation. By using this method, the dataset was divided into ten folds. The model was refitted ten times, considering in each refit nine folds for fitting the model and the remaining fold for prediction. The root mean squared error (RMSE) was calculated for each refit and the average value considering all the validation process was obtained.

3 Results

3.1 Field data description

After completing the data collection and reduction, 9346 interactions with other vehicles were registered from the recordings. Anomalous data due to equipment malfunction or data collected at intersections were excluded. Finally, 2346 overtaking manoeuvres were correctly recorded. In this study, only the manoeuvres performed by passenger cars and with all the variables registered were considered, thus, the final dataset was formed by 2028 overtaking manoeuvres.

The flying manoeuvres represented 79% of these overtaking events (1592 manoeuvres), while 9% (192) were accelerative manoeuvres. The rest were piggy backing manoeuvres, where the vehicle performed the overtaking while following another vehicle. Piggy backing manoeuvres were excluded from the analysis because of the involvement of the lead vehicle that could have affected the driver behaviour (Rasch et al. 2020b).

The distribution of overtaking durations for each overtaking strategy is shown in Figure 3. The mean value of the overtaking duration for flying manoeuvres was 4.81 s (SD 2.41 s), while for accelerative manoeuvres, the mean overtaking duration was 6.88 s (SD 2.26 s). Generally, flying manoeuvres generated lower overtaking duration than accelerative. This is explained by the fact that accelerative manoeuvres start from a following state to the bicycles, so they are usually performed at a lower speed.

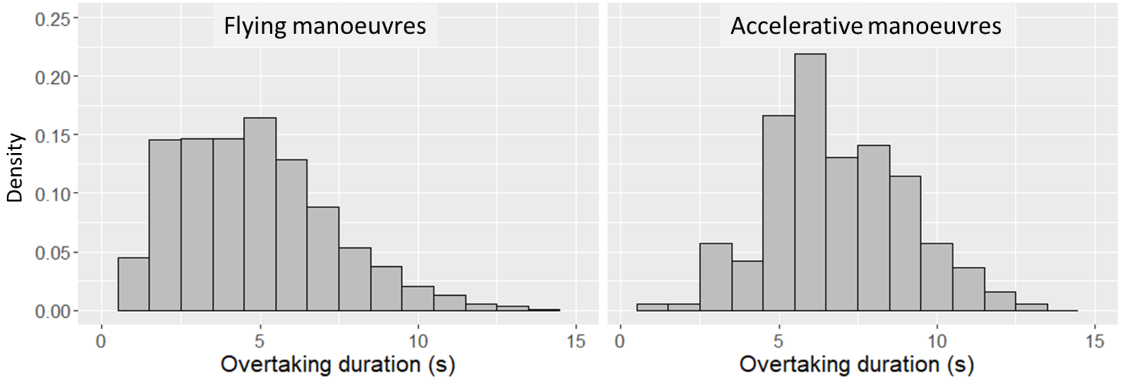


Figure 3. Distribution of overtaking duration (s) for each overtaking strategy.

Table 3 shows the overtaking duration values considering the variables obtained from the field data collection for flying and accelerative manoeuvres.

Table 3. Overtaking duration results from field data for flying and accelerative manoeuvres.

	Flying manoeuvres				Accelerative manoeuvres			
Variables	Obs.		Overtaking duration (s)		Obs.		Overtaking duration (s)	
	N	(%)	Mean	SD	*N*	(%)	Mean	SD
Lane width (m)								

3	*482*	30%	4.38	2.29	*60*	31%	6.23	1.96
3.2	*726*	46%	4.80	2.45	*73*	38%	7.30	2.55
3.5	*384*	24%	5.35	2.38	*59*	31%	7.00	2.04
Shoulder width (m)								
0	*136*	9%	6.99	2.26	*44*	23%	7.32	2.10
1	*389*	24%	5.62	2.46	*36*	19%	7.97	2.70
1.5	*1067*	67%	4.23	2.15	*112*	58%	6.35	2.01
Speed limit (km/h)								
60	*482*	30%	4.38	2.29	*60*	31%	6.23	1.96
70	*136*	9%	6.99	2.26	*44*	23%	7.32	2.10
80	*726*	46%	4.80	2.45	*73*	38%	7.30	2.55
100	*248*	16%	4.46	1.93	*15*	8%	6.07	1.58
AADT (vehicles/day)								
4733	*136*	9%	6.99	2.26	*44*	23%	7.32	2.10
4797	*248*	16%	4.46	1.93	*15*	8%	6.07	1.58
5542	*337*	21%	3.86	2.07	*37*	19%	6.65	2.25
6380	*389*	24%	5.62	2.46	*36*	19%	7.97	2.70
16310	*482*	30%	4.38	2.29	*60*	31%	6.23	1.96
Number of cyclists								
1	*366*	23%	3.73	2.04	*17*	9%	5.76	1.86
2	*542*	34%	4.42	2.15	*51*	27%	6.16	2.06
4	*466*	29%	5.05	2.25	*65*	34%	6.66	2.07
10	*218*	14%	7.03	2.40	*59*	31%	8.05	2.29
Group configuration								
In line	*1019*	64%	4.62	2.45	*78*	41%	7.21	2.35
Two-abreast	*573*	36%	5.14	2.30	*114*	59%	6.65	2.18
Horizontal alignment								
Left curve	*126*	8%	4.31	2.05	*25*	13%	7.04	2.09
Right curve	*123*	8%	4.28	2.15	*9*	5%	6.67	1.12
Tangent	*1343*	84%	4.90	2.45	*158*	82%	6.86	2.34
Oncoming vehicle presence								
No	*1096*	69%	5.34	2.45	*154*	80%	7.21	2.25
Yes	*496*	31%	3.62	1.84	*38*	20%	5.53	1.77
Opposing lane invasion								
No	*368*	23%	2.86	1.62	*13*	7%	4.77	2.20
Partial	*1024*	64%	5.04	2.15	*117*	61%	6.43	1.94
Complete	*200*	13%	7.18	2.18	*62*	32%	8.16	2.20
Overtaking vehicle speed								
km/h	Mean = 67.43		SD = 15.63		Mean = 50.03		SD = 9.65	
Lateral clearance								
m	Mean = 1.81		SD = 0.48		Mean = 1.94		SD = 0.49	

In Table 3, different relationships between the overtaking duration and the variables can be seen. There are some variables for which an increase in them presented a clear increase in the overtaking duration, such as the number of cyclists in the group. Other variables did not present a clear relationship, such as the speed limit or the AADT of each road.

3.2 Overtaking duration models

The eight models showed in Table 2 were fitted for flying and for accelerative manoeuvres. All models converged with large effective sample sizes. Trace plots were inspected visually, showing no signs of divergences, and the Rhat values equal to 1 suggested proper chains convergence (Bürkner, 2017). The results of the model comparison using the LOOCV are shown in Table 4.

Table 4. Results from Bayesian model comparison using the leave-one-out cross-validation. M7F and M6A were used as the baseline for all comparisons.

Flying manoeuvres			Accelerative manoeuvres		
Model	ELPD_diff	SE_diff	Model	ELPD_diff	SE_diff
M7F	-	-	M6A	-	-
M6F	-10	17.5	M7A	-2.3	7.7
M5F	-22	7	M4A	-6.1	3.4
M4F	-26.6	19.7	M5A	-11.4	7.8
M2F	-150.7	22.8	M2A	-11.8	7
M1F	-151.6	22.9	M1A	-12.7	6.9
M3F	-185.5	18.1	M3A	-25.9	10.4
M8F	-868.3	27.5	M8A	-166.7	10.2

From the LOOCV comparison, the best model for the flying manoeuvres was the M7F. This model included all the factors and used the log-normal distribution. For the accelerative manoeuvres, the models M6A and M7A presented the best results, and there was a small difference between them. In fact, the difference in ELPD was within the range of the standard error for M6 and M7 in both strategies. Therefore, the log-normal and Weibull distributions both resulted in good fits of the overtaking duration models. To compare the results for both strategies, the model M7A was selected to increase the parallelism with the flying model (since models M7F and M7A included the same factors and had the same distribution). The average RMSE obtained after 10-fold-cross validation was 1.88 s for flying manoeuvres (M7F) and 1.86 s for accelerative manoeuvres (M7A).

The model for flying manoeuvres had a higher Bayesian R^2 mean estimate compared to the model for accelerative manoeuvres, however, within the uncertainty of the estimate (Table 5). The parameter posterior distributions (mean, standard error, and 95% credible interval) are shown in Table 5.

Table 5. Parameter distributions of the models for overtaking duration considering each overtaking strategy. Mean, standard error (SE) and lower and upper values of the 95% credible interval (l-95% CI and u-95% CI, respectively), reported for each parameter. σ is the standard deviation parameter of the log-normal distribution. CIs which do not include zero are represented in bold.

	Flying manoeuvres model (M7F)				Accelerative manoeuvres model (M7A)			
	Mean	SE	l-95% CI	u-95% CI	Mean	SE	l-95% CI	u-95% CI
Bayesian R^2	0.55	0.01	0.53	0.57	0.47	0.04	0.39	0.54
Parameters								
β_0	1.98	0.42	**1.14**	**2.79**	2.99	1.01	**1.04**	**4.97**
β_{Lane}	-0.55	0.16	**-0.86**	**-0.23**	-0.27	0.37	-1.01	0.45
$\beta_{\mathrm{Shoulder}}$	-0.66	0.05	**-0.76**	**-0.55**	-0.11	0.13	-0.36	0.13
β_{Slimit}	0.02	0.00	**0.01**	**0.02**	0.00	0.01	-0.02	0.01
$\beta_{\mathrm{scaleAADT}}$	0.19	0.03	**0.13**	**0.25**	-0.08	0.07	-0.22	0.06
$\beta_{\mathrm{Cyclists}}$	0.06	0.00	**0.05**	**0.07**	0.04	0.01	**0.03**	**0.06**
β_{ConfP}	0.17	0.02	**0.12**	**0.21**	-0.07	0.05	-0.16	0.02
$\beta_{\mathrm{HAlignRight}}$	0.00	0.05	-0.10	0.10	-0.07	0.12	**-0.30**	**0.15**
$\beta_{\mathrm{HAlignTangent}}$	0.12	0.04	**0.04**	**0.20**	-0.04	0.06	**-0.18**	**0.08**
β_{OncVis}	-0.18	0.03	**-0.24**	**-0.12**	-0.17	0.06	**-0.29**	**-0.04**
β_{Ovspeed}	-0.01	0.00	**-0.01**	**0.00**	-0.01	0.00	**-0.02**	**-0.01**
$\beta_{\mathrm{Clearance}}$	0.48	0.02	**0.44**	**0.53**	0.33	0.05	**0.25**	**0.42**
σ	0.41	0.01	0.40	0.43	0.29	0.02	0.26	0.32

As shown in the parameter distributions presented in Table 5, the direction of each effect on the overtaking duration is clear. However, its magnitude can be hard to interpret since the regression coefficients are on the log scale. To ease interpretation, the effects were transformed and plotted on the original scale using conditional effects plots (Bürkner, 2019). Figure 4 shows the conditional effects of each variable on the overtaking duration for the flying and the accelerative manoeuvres. When creating conditional effects for a particular variable, the values of all other variables are conditionalised on the mean for numerical variables and the reference level for categorical variables. These plots show the expected overtaking duration response as predicted by model M7F and M7A for flying and accelerative manoeuvres, respectively. In Figure 4, the shaded area represents the 95% credible intervals around the estimates.

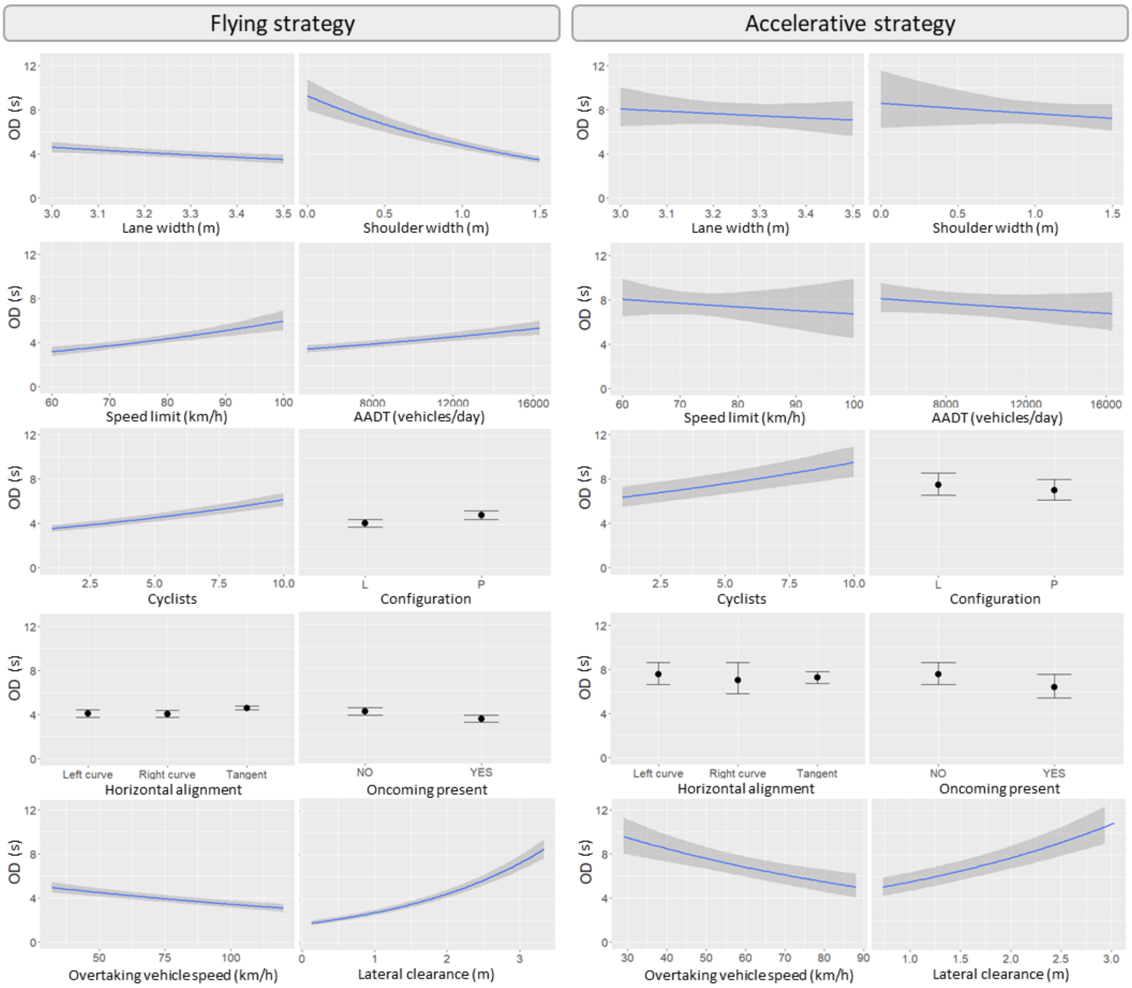


Figure 4. Conditional effects for each variable on the overtaking duration (OD), i.e., all other categorical variables being set to their reference level and numerical variables being set to their mean, considering flying and accelerative manoeuvres. The solid line represents the mean and the shared area represents the 95% credible interval.

3.2.1 Flying manoeuvres model

When considering the results of the flying manoeuvres, only the parameter distribution of the horizontal alignment for the right curve included zero inside the 95% CI. This result indicates that the overtaking duration was similar for overtakings performed in a right and a left curve. The rest of the parameters for flying manoeuvres have a notable effect on the overtaking duration, i.e. their distributions did not include zero. An increase in lane width and shoulder width resulted in a decrease in overtaking duration. However, shoulder width has a stronger effect than lane width. An increase in speed limit and AADT produced higher overtaking durations. Considering the group of cyclists, when a group was formed by a higher number of cyclists, the overtaking duration was larger, and when the cyclists rode two-abreast, the overtaking duration was larger as well. About the factors related to the horizontal alignment, when the manoeuvre was performed on a tangent segment, the overtaking duration was higher than when it was produced in a curve. The presence of an oncoming vehicle generated a lower overtaking duration. The overtaking vehicle speed had an inverse relation to the overtaking duration. The lateral clearance had a considerable influence on the overtaking duration, with higher clearance associated with larger overtaking duration.

The results of the overtaking duration model for flying manoeuvres showed an opposite effect for lane width than the obtained from observations. Furthermore, the lane width had a weak effect compared to shoulder width. If there is a shoulder, the position of the cyclists within the cross-section of the road is different. These results suggest that the width of the lane and the shoulder should be considered together for each road segment since it is the total space where drivers and cyclists interact, and considering it together may explain better the phenomenon. Additionally, considering only the lane width can lead to erroneous results, since in this study, the narrowest and the widest road segments had the same lane width.

Therefore, a new model (M7FN) was fitted considering the lane and shoulder widths together. This model was based on model M7F, by deleting the lane and shoulder widths variables and introducing the lane and shoulder width considering together (LSWidth). The distributions of the parameters in the model M7FN only presented changes for the intercept parameter ($\beta_{0,M7FN} = 2.32, [2.04, 2.59]\ 95\%\ \mathrm{CI}$), and the distribution of LSWidth presented a stronger effect on the overtaking duration than when the lane and shoulder widths were considered separately ($\beta_{LSWidth,M7FN} = -0.68, [-0.78, -0.59]\ 95\%\ \mathrm{CI}$). The conditional effects of all the other factors presented the same values in both models. M7FN was slightly better than M7F within standard error, based on the results of LOOCV comparison (ELPD_diff=-0.6, SE_diff=0.8), while the Bayesian R^2 was similar for both models.

3.2.2 Accelerative manoeuvres model

Accelerative manoeuvres presented more parameters with 95% CI that included zero, indicating that these parameters did not have a clear effect on the overtaking duration. In accelerative manoeuvres, such parameters were related to the road segment: the lane and shoulder widths, the speed limit and the AADT. Regarding the parameters related to the group of cyclists, the number of cyclists in the group had a clear effect on the overtaking duration such that a higher number of cyclists produced a longer duration of overtaking. The configuration in which the group of cyclists rode had a weak effect on the overtaking duration. The horizontal alignment where the overtaking was performed were unrelated to the overtaking duration for accelerative manoeuvres. The presence of an oncoming vehicle during the manoeuvre had a clear effect on the overtaking duration, presenting lower values of overtaking duration when an oncoming vehicle was visible. Finally, the overtaking vehicle speed and the lateral clearance affected the overtaking duration in such a way that higher overtaking speeds and lower lateral clearances presented a reduction in the overtaking duration.

4 Discussion

Flying manoeuvres (79%) were more prevalent than accelerative (9%), indicating that in most cases, drivers can overtake cyclists easily without having to follow them before overtaking. Flying manoeuvres are preferred by drivers because they are performed without speed reduction, then they penalise the traffic operation less. Most of the naturalistic previous studies presented the majority of flying manoeuvres (Dozza et al., 2016; Kovaceva et al., 2019). Flying manoeuvres were performed with higher overtaking vehicle speeds and lower lateral clearances, so the overtaking duration was lower than accelerative ones. These results are in correspondence with Dozza et al. (2016), Bianchi Piccinini et al. (2018) and Kovaceva et al. (2019), who concluded that accelerative manoeuvres are safer than flying because these manoeuvres are performed at lower speeds, and the driver has better control of the interaction with the oncoming vehicle and leaves higher clearances to the cyclists. The overtaking duration values obtained in this study, considering only one cyclist, agrees with the obtained by Dozza et al. (2016), who concluded that accelerative manoeuvres took longer than flying. Asaithambi and Shravani (2017) realised a study of overtaking manoeuvres in mixed traffic on rural roads and also obtained larger overtaking durations for accelerative than for flying types of manoeuvres.

Flying manoeuvres implied a lower percentage of opposing lane invasion (77%) in front of accelerative manoeuvres (93%); this fact, additionally to the lower overtaking duration, shows that these manoeuvres were preferred by drivers. However, flying manoeuvres were performed at higher speeds and lower lateral clearances, and they presented a higher percentage of oncoming vehicle presence (31%) than accelerative manoeuvres (20%). These last results emphasise the danger of flying manoeuvres for cyclists.

The main geometric characteristics of the road associated with the overtaking duration were the lane and shoulder widths. On two-lane rural roads, cyclists ride on the shoulder or on the right edge of the lane if the shoulder is inexistent or impassable. For flying manoeuvres, the effect of the shoulder width was stronger than the lane width since the shoulder width controls the cyclist lateral position within the driver’s field of safe travel. Previous research has shown that with an overlap between the overtaking vehicle’s and the cyclist’s paths in the approaching phase, safety metrics during the manoeuvre were reduced, and drivers preferred accelerative manoeuvres (Rasch et al., 2020). However, on two-lane rural roads without cycle lanes, considering the lane and shoulder widths separately can lead to wrong conclusions since the total space where motorised vehicles and bicycles interact is formed by the widths of the lane and shoulder considered together. Therefore, regarding the effect of the lane and shoulder widths considering together (M7FN), wider rural roads presented lower overtaking durations. On wider roads, cyclists ride on the shoulder, making it easier for the driver to perform the manoeuvre. Furthermore, wider rural roads usually presented larger lateral clearance as verified in various studies (Llorca et al., 2017; Debnath et al., 2018; Feng et al., 2018; Chapman and Noyce, 2014; Bella and Silvestri, 2019; Mecheri et al., 2020). The effect of the shoulder width was not clear in previous studies (Dozza et al., 2016; Mecheri et al., 2020; García et al., 2015). However, the results of this study presented a strong effect of the shoulder width on the overtaking duration, especially for flying manoeuvres, such that a wider shoulder reduced the overtaking duration. A study realised by Llorca et al. (2017) indicated that the provision of wider shoulders could be an appropriate measure to ensure safe overtaking manoeuvres considering the higher lateral clearance. Moreover, when analysing the interactions between motorised vehicles and cyclists on two-lane rural roads, the total space where they interact has to be considered as a whole (i. e. the lane and shoulder widths). Therefore, wider roads, especially with wider shoulders, offer higher lateral clearance and lower overtaking duration, then, they can be considered a safe countermeasure from the cyclist's and drivers' point of view.

The effect of the speed limit and the AADT of the road had the opposite sign for flying and for accelerative strategies. Nevertheless, in accelerative manoeuvres, the effect of the parameters related to the road segment seems unrelated to the overtaking duration since the 95% CI includes zero (Table 5), resulting in the wider shaded areas in Figure 4. In the accelerative strategy, overtaking usually starts from a low vehicle speed, since the vehicle was following the bicycles, and most of the manoeuvres were performed without an oncoming vehicle present, then the speed limit and the AADT had a poor effect on the duration. Rubie et al. (2020) stated that it is potentially difficult to interpret the effects of posted speed limits on lateral clearances because higher speed limits are not only associated with higher motor vehicle speeds, but also with different road types, passing strategy and lane widths. In fact, the effect of the speed limit is contrary to the overtaking vehicle speed for flying manoeuvres. Mackenzie et al. (2021) obtained larger passing distances in roads with higher speed limits; this result agrees with the obtained in the present study since larger lateral clearances can be related to higher overtaking durations.

Regarding the configuration of the group of cyclists, in both strategies, when a higher number of cyclists were in the group, the overtaking duration was larger. This result agrees with García et al. (2016) and Debnath et al. (2018), who obtained for individual cyclists lower passing distance than for a group. The number of cyclists in the group also influences the strategy choice, such that with more cyclists in the group, more accelerative manoeuvres were observed. About the group configuration, in flying manoeuvres, the two-abreast configuration presented larger overtaking durations, since cyclists occupy more space in the lane and the driver had to evade farther into the opposing lane. However, in accelerative manoeuvres, the effect of two-abreast configuration had a weak effect on the overtaking duration, and when the cyclists rode two-abreast, lower overtaking durations were registered. This fact can be explained because accelerative manoeuvres started from a low vehicle speed, and then, less time was needed to overtake a two-abreast configuration meaning a shorter length of the group.

The horizontal alignment where the overtaking manoeuvres were performed had a weak effect on overtaking duration for accelerative manoeuvres. Instead, for flying manoeuvres, larger overtaking durations were registered in tangents than in curves, due to the higher available visibility on tangent sections, which is associated with larger opposite lane invasions and higher lateral clearances. This result is in line with Llorca et al. (2017), who obtained higher lateral spacing and speed on tangent sections compared to curves, but opposite to Bella and Silvestri (2019).

The presence of oncoming traffic has been defined in studies from Dozza et al. (2016), Bianchi Piccinini et al. (2018) and Rasch et al. (2020) as the principal factor affecting safety margins. Bianchi Piccinini et al. (2018) stated that drivers who completed the overtaking manoeuvre without waiting for an oncoming vehicle to pass reduced their minimum safety margins in the steering away and passing phases. The same result was obtained by Rasch et al. (2020), who stated that safety metrics during the entire manoeuvre decreased when the time gap to the oncoming vehicle was short. These results agree with the present study where shorter durations of overtaking were registered when an oncoming vehicle was present for both strategies. However, 80% of the accelerative manoeuvres were performed without an oncoming vehicle present in front of 69% of the flying manoeuvres, demonstrating that the presence of an oncoming vehicle induced more drivers to choose the accelerative manoeuvre (Bianchi Piccinini et al., 2018); already in accelerative manoeuvres, drivers usually wait for the oncoming vehicle to pass to start the manoeuvre.

The overtaking vehicle speed and the lateral clearance had the same effect on both strategies; larger overtaking durations were observed with lower vehicle speeds and higher lateral clearances. Nevertheless, for flying manoeuvres, a higher mean value and a narrow credible interval of the parameter of lateral clearance was obtained, indicating a strong effect of the lateral clearance on the overtaking duration for flying manoeuvres. These results agree with Bella and Gilusano (2020), who analysed the overtaking manoeuvre performed by motorcycles, obtaining larger overtaking durations when higher lateral distances and lower speed differences were presented. Llorca et al. (2017) and López et al. (2020) constated that the subjective risk perception of cyclists was related to the combination of overtaking speed and lateral clearance during the overtaking manoeuvre.

The overtaking duration models developed can be used to obtain predictive values considering other cyclist grouping configurations. These predictions can be used as input to traffic microsimulation models to calibrate the effective lengths of other groups of cyclists different from those observed, increasing the validity of the microsimulation studies (Moll et al., 2021).

The results of this study are limited to the geometry and traffic characteristics of the roads where the data were collected, and also to the factors analysed. As further research, it will be interesting to collect data on roads with a higher presence of heavy vehicles and with other geometric characteristics such as cycle lanes, and include some additional factors with an important role in the overtaking manoeuvre such as the available visibility. Future research should also determine the relationship between the subjective risk perception of cyclists and drivers and the duration of the overtaking manoeuvre.

5 Conclusions

In this study, the duration of overtaking to cyclists on two-lane rural roads was modelled. Models were based on naturalistic data of overtaking events between motorised vehicles and bicycles obtained using instrumented bicycles. The sample of overtaking manoeuvres analysed (1592 flying and 192 accelerative), and the variability of road segments and cyclist grouping characteristics, allowed to obtain reliable and clear conclusions. The overtaking duration to cyclists was modelled for flying and accelerative manoeuvres using Bayesian statistics. The factors analysed were related to the road segment (lane and shoulder width, speed limit, and AADT); the cyclist grouping (number of cyclists and configuration); and the overtaking manoeuvre (horizontal alignment, oncoming vehicle presence, vehicle speed, and lateral clearance). Different models were fitted and compared, obtaining the best results for the models that considered all the factors and the log-normal response distribution.

Results showed that flying manoeuvres (79%) were more prevalent than accelerative (9%), and they were performed with higher speeds and lower lateral clearances and, therefore, presented lower overtaking durations. The lane and shoulder widths have to be considered together since it is the total space where cyclists and drivers interact. Wider roads presented lower overtaking durations. However, the factors related to the road segment had a poor effect on accelerative manoeuvres. Groups formed by a higher number of cyclists presented larger overtaking durations, while two-abreast configuration had an opposite effect on the duration for both strategies. Flying manoeuvres performed in a tangent segment had a higher duration than in a curve; nevertheless, the horizontal alignment had a poor effect on the overtaking duration for accelerative manoeuvres. The presence of an oncoming vehicle decreased the overtaking duration, whereas a decrease in vehicle speed and an increase in lateral clearance increased the duration of overtaking.

The results of this study allow researchers to better understand the phenomenon of interactions between motorised vehicles and bicycles on rural roads. By using the developed predictive models, it is possible to obtain overtaking durations varying the conditions of the road and the group of cyclists. These results can be used as an input to traffic microsimulation models to analyse the safety and traffic operation on two-lane rural roads. The results presented in this paper can also be used to improve the infrastructure design and manage traffic conditions by regulating the motorised vehicles speed or suggesting safer cyclist grouping configurations to obtain safer and effective rural roads that integrate all users.

CRediT authorship contribution statement

Sara Moll: Methodology, Data collection, Investigation, Software, Formal analysis, Writing - original draft. **Griselda López:** Conceptualization, Methodology, Data collection, Investigation, Formal analysis, Writing - original draft, Supervision. **Alexander Rasch:** Methodology, Investigation, Software, Formal analysis, Writing - review & editing. **Marco Dozza:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - review & editing, Supervision. **Alfredo García:** Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was part of the project “Improvement of safety and operation of two-lane rural roads with cyclists (Bike2Lane)” (TRA2016-80897-R) funded by the Spanish Ministry of Science and Innovation. The research collaboration was funded by the Agencia Estatal de Investigación “Ayudas para contratos predoctorales para la formación de doctores 2017” (BES-2017-080474).

The authors would like to thank the General Directorate of Public Works and Transportation of the Valencian Government, the Road Department of the Valencian Provincial Council, and the General Directorate of Traffic of Spain, for their cooperation in field data gathering.

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