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Safety analysis of motorcyclists' overtaking maneuvers

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ABSTRACT

This paper aims to investigate the overtaking behavior of motorcyclists in a suburban environment. The goal is to model overtaking duration, identify the factors influencing it, and determine the likelihood of a rider overtaking a vehicle while maintaining critical lateral clearance. Riding data were collected using a passenger car equipped with cameras and a GPS device, which recorded videos of motorcyclists performing maneuvers to overtake it. This setup allowed for capturing natural motorcyclist behavior and avoided the potential limitations of instrumented motorcycle studies, such as bias due to participants being aware of their involvement in the experiment. A total of 119 overtaking maneuvers were recorded. A methodology combining digital image processing algorithms and GPS analysis was employed to characterize the recorded maneuvers. Survival and logistic analyses were then conducted to model the duration of overtaking and lateral clearance, respectively. The hazard-based duration model indicated that the duration of a motorcyclist's overtaking maneuver is influenced by the final longitudinal distance between the motorcycle and the passed vehicle at the end of the maneuver. Other factors include the speed difference between the motorcycle and the front vehicle at the same instant, and the initial Time-To-Collision (TTC) between the motorcycle and the front vehicle at the beginning of the overtaking. The logistic regression analysis revealed that the probability of overtaking a vehicle with a lateral clearance below the critical threshold increases when the rider does not invade the opposite lane during the overtaking maneuver when a vehicle in the opposite lane induces the motorcyclist to return to the right lane, and as the duration of the overtaking maneuver increases. This research provides valuable contributions to understanding motorcyclist behavior during overtaking maneuvers, aiding in the development of more realistic microsimulation models that account for actual rider behavior. Additionally, the study contributes to the development of Advanced Rider Assistance Systems aimed at guiding motorcyclists to make safer overtaking decisions and reduce significant risk exposure from complex overtaking maneuvers.

1. Introduction

Motorcyclists face significant risks in the event of road accidents. The high-risk condition they are exposed to is highlighted by incident data concerning this user category, appropriately considered Vulnerable Road Users (VRU).

Motorcycle riders comprised 16 % of the recorded road fatalities in Europe in 2020 (European Commission, 2023). This statistic is notably higher in Italy, where, in 2022, 24.7 % (781 deaths) of road fatalities were motorcycle riders, indicating an increase in motorcyclist fatalities compared to the pre-pandemic year (2019) by + 11.9 % (ACI-ISTAT, 2023; European Commission DG MOVE – CARE, 2023).

The high vulnerability of motorcyclists has garnered increasing attention and concern within the scientific community and among traffic regulatory authorities. This has resulted in research initiatives (e.g. SaferWheels study, 2018) and research projects under the latest European research programs (e.g., InDeV project, 2015; PIONEERS project, 2018), as well as the implementation of measures such as personal protective equipment and on-board systems aimed at enhancing protection and safety for this vulnerable group.

Although the research efforts have undoubtedly brought about significant improvements in the road safety of motorcyclists, the aforementioned incident data indicate that further research activities are still needed. This need is also imperative to contribute significantly to the goal of halving road deaths by 2030 compared to 2019, as expected by the European Union (European Commission and Directorate-General for Mobility and Transport, 2020), and the even more ambitious goal set by Italy to reduce the number of casualties among motorized two-wheel

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users by 55 % by 2030 (Ministero delle Infrastrutture e della Mobilità Sostenibili-MIMS, 2022).

For enhancing the road safety of motorcyclists, the examination of their behavior during riding is crucial. Specifically, considering that the overtaking maneuver performed by riders is a complex and highly risky task (RoSPA, 2017), it becomes particularly relevant to study and analyze the motorcyclist's behavior while executing such maneuvers.

While there is extensive literature on the behavior of car drivers during overtaking (Bella, 2011; Bella and Silvestri, 2017; Llorca and García, 2011; Vlahogianni, 2013), research on the overtaking behavior of motorcyclists is notably limited in academic literature.

During the last decade, several methods have been successfully applied by researchers to investigate the parameters related to the overtaking maneuvers of motorcyclists, including the use of trajectory data collected by video recordings in an urban context (Vlahogianni, 2014), as well as moving car method (Asaithambi and Shravani, 2017), and video -based computer vision techniques to track road users, to collect trajectories, and measure lateral distance (Guo et al., 2020). On the other hand, other researchers have conducted field experiments using instrumented motorcycles with cameras and GPS. For this purpose, Bella and Gulisano (2020) carried out a survey using an instrumented motorcycle on a two-lane suburban road to collect data on motorcyclists' behaviors during overtaking and modeled the duration through survival analysis. Similarly, Keshari et al. (2024) used instrumented motorcycles to investigate overtaking behavior on a two-lane undivided road section, identifying factors affecting the total overtaking duration through a hazard-based duration approach.

Several parameters have been analyzed in the literature to assess and identify the criticality of overtaking maneuvers, including overtaking duration and lateral clearance.

More specifically, overtaking duration represents the time interval required to execute the overtaking maneuver, during which riders are exposed to significant hazards (Asaithambi and Shravani, 2017). During the initial phase of the maneuver, the risk of rear-end collisions drastically increases due to reduced time headway with the preceding vehicle (Hegeman et al., 2005; Polus et al., 2000; Rajalin et al., 1997). In addition, the probability of collision with an oncoming vehicle increases during the invasion of the opposite lane (Richter et al., 2016). Numerous studies have investigated the factors influencing overtaking duration for various vehicle types, including car drivers (Moll et al., 2021; Vlahogianni, 2013) and non-motorized vehicles (Liu et al., 2021b). However, limited studies focus on parameters affecting motorcyclists' overtaking maneuvers. Asaithambi and Shravani (2017) examined overtaking maneuvers on two-lane roads for different user categories, finding that the total overtaking duration for maneuvers performed by motorcyclists and car drivers was similar and shorter compared to those of other user categories. More recently, a model developed by Bella and Gulisano (2020), based on real data collected by an instrumented motorcycle, showed that overtaking duration for motorcyclists primarily depends on the initial distance and speed difference with the initial lateral distance and final distance having a minor impact. Keshari et al. (2024) assessed the factors influencing the overtaking duration of motorcycles on a two-lane undivided road section. Results from a hazard-based duration model showed that overtaking duration was positively related to the initial gap, final gap, speed of the overtaken vehicle, and multiple overtaking. Conversely, the speed of the overtaking motorcycle had a negative impact on overtaking duration. One of the main limitations of these studies is that the riders are aware of the experimental activities, as they operated instrumented motorcycles.

Another significant indicator of risk is the lateral clearance, representing the minimum distance maintained between passing and passed vehicles (Moll et al., 2021; Rubie et al., 2020). However, research on lateral clearance during overtaking maneuvers by motorcyclists is still limited. In urban environments, the factors influencing the adoption of short lateral distances during overtaking maneuvers include adjacent lane spacing, speed differences, and the presence of platoons (Vlahogianni, 2014). This study highlights that these elements significantly affect overtaking behavior, emphasizing the importance of lane configurations and traffic dynamics. In contrast, Ibrahim et al. (2018) specifically examined exclusive motorcycle lanes, finding that lane width and roadside configurations are crucial in determining the lateral positioning of motorcycles during overtaking. Their research underscores how infrastructure design directly impacts overtaking safety in dedicated motorcycle lanes. Comparatively, Guo et al. (2020) expanded the analysis to various types of two-wheelers, including e-bikes, e-scooters, and bicycles. Their findings reveal that the acceptance of critical lateral distances is positively influenced by factors such as the type of two-wheeler, platoon occurrence, and the yaw rate ratio. Conversely, the presence of heavy vehicles and speed differences negatively impact the probability of maintaining safe lateral distances.

In summary, the literature above highlights the following gaps: few studies have been conducted on overtaking maneuvers of motorcyclists, mostly referring to urban arterial, with low speed and high flow conditions or specific cross sections with lanes dedicated to two-wheelers. In addition, one of the most significant limitations is related to the awareness of the riders during the experimental activities, as previously mentioned.

Given the above, the primary objective of this research is to examine the overtaking behavior of motorcyclists in a suburban environment by modeling overtaking duration and identifying the factors influencing it, as well as determining the likelihood that the rider will execute an overtaking maneuver while adopting a critical lateral clearance. This research seeks to provide a valuable contribution to the assessment of the risk conditions associated with overtaking maneuvers by motorcyclists in such road environments, which is essential for the development of countermeasures focused on mitigating factors related to risky behavior.

To address existing gaps found in the literature, this study employs a method where data and video recordings are collected using an instrumented car. The main novelty of this study lies in its ability to capture the behavior of riders who are unaware of the experiment, ensuring that their driving style remains unchanged and providing more reliable insights into rider behavior during overtaking maneuvers.

The subsequent section of the paper outlines the research methodology (Section 2), encompassing field data collection, data processing using a digital image processing algorithm, and data analysis employing a hazard-based duration approach and logistic regression to model overtaking duration and lateral clearance, respectively. This section is followed by the results section (Section 3) and discussion section (Section 4), which discusses the outcomes of the proposed overtaking duration model and the lateral clearance model, culminating in the conclusions.

2. Methodology

In this section, the methodology used in the experiment is presented. After introducing the field data collection in section 2.1, details about the variables of interest are provided in section 2.2. Then, the digital image processing algorithm for the data processing and the data recorded during the events were described in section 2.3. Finally, statistical procedures used for modeling the overtaking duration and the lateral clearance are detailed in section 2.4.

2.1. Field data collection

The field experiment was conducted along a two-lane rural suburban road in Rome, SP8 Via Ostiense, one of the most critical roads for motorcycles, according to Rome's Road Safety Plan. The investigated section consists of a single long tangent (4 km) with a null grade and a speed limit of 60 km/h. The cross-section is 9.50 m wide, formed by two 3.50 m wide lanes and two paved shoulders 1.25 m wide, according to the Italian road design guidelines.

Riding data were collected using a car moving method: an instrumented passenger car (test vehicle) was driven along the road to make other vehicles overtake it. The overtaking maneuvers performed by the motorcycles were recorded using 4 cameras (1 GoPro Hero8 and 3 GoPro Hero3) installed inside the vehicle on unobtrusive mounts, making them difficult for the motorcyclist to see during the overtaking maneuver.

More specifically, one camera was installed at the rear of the vehicle to capture the initial phase of the overtaking maneuver, and one camera was positioned at the front of the vehicle to record the other phases of the maneuver. In addition, two further cameras were placed on the left side of the vehicle to record the phase of overtaking with the motorcycle alongside the vehicle, which was not visible from the rear and front cameras (Fig. 1).

The frontal camera (GoPro Hero8) had a built-in Global Positioning System (GPS) which allowed the collection of position and speed data of the test vehicle.

The video recordings from the front and rear cameras were utilized to derive the variables of interest for the overtaking maneuver, employing the procedure outlined in Section 2.3 (Data Processing). The video recordings acquired from the lateral cameras were used to observe rider behavior during the overtaking phase when the rider was alongside the instrumented passenger car. Such video recordings allowed us to confirm that the motorcyclist did not change his lateral position between the moment when the front wheel of the motorcycle reached the front wheels of the instrumented vehicle and the moment when the motorcycle was visible in the video recorded by the front camera, which allowed us to measure the lateral clearance.

To limit the impact on the behavior of passing riders and to keep the overtaking conditions uniform among the motorcyclists, the instrumented vehicle traveled at a constant speed of about 50 km/h (the mean value was 48 km/h, as reported in Table 2), centered in the driving lane. The vehicle's position in the lane was not controlled by any device but relied on the driver's skill. The instrumented vehicle was always driven by the same driver to minimize potential changes in driving style and not compromise the reliability of the measurements taken during the motorcyclists' overtaking maneuvers.

The data collection was conducted on weekdays between 9:00 am and 12:00 pm, in dry pavement conditions. This period was chosen to avoid peak traffic conditions that would have prevented overtaking. The traffic density was sufficiently low, allowing the riders to overtake the instrumented vehicle, and reasonably constant, allowing to remove the effect of this potentially confounding factor on the overtaking maneuver.

2.2. Overtaking maneuver and variables of interest

The beginning and the end of the overtaking maneuver were determined according to the motorcycle's trajectory. The overtaking was assumed to start (t_i) when the steering angle of the motorcycle was greater than 10 degrees with respect to the straight trajectory. Similarly, the overtaking ended (t_f) when the rider, returned to the right lane after the overtaking and adopted a steering angle lower than 10 degrees with respect to the straight trajectory (Bella and Gulisano, 2020; Bella and Silvestri, 2017).

The entire overtaking process was then divided into three different phases:

- Phase 1: from the moment the motorcycle begins the overtaking maneuver to the moment it crosses the centerline.
- Phase 2: identified as the time interval in which the motorcycle occupies the opposite lane.
- Phase 3: from the moment the motorcycle crosses the centerline to go back to the right lane until the moment in which the motorcycle ends the maneuver.

The overtaking duration (*OD*) and the lateral clearance (*H*) are the two road safety variables analyzed in this research. The overtaking duration *OD* was calculated as:

$$OD = t_f - t_i$$

As for the lateral clearance *H*, this is defined as the distance between the motorcycle axis and the left wheel of the instrumented vehicle, at the moment when the front wheel of the motorcycle reaches the front wheels of the instrumented vehicle. However, this moment was only visible from the lateral cameras and not from the rear or front cameras. It is important to note that the recordings from the lateral cameras do not allow for the direct estimation of H, as the methodology used in the study (see Section 2.3) relies on determining the vanishing point, which cannot be obtained from images captured by the lateral cameras.

For this reason, to better compare the findings of the existing literature with those of the present study, the assumption was made that the motorcyclist did not change his lateral position between the moment when the front wheel of the motorcycle reached the front wheels of the instrumented vehicle and the moment when the motorcycle was visible in the video recorded by the front camera. This assumption allowed for the evaluation of the lateral clearance H using the methodology proposed in Section 2.3. It should be noted that the time interval between these two positions of the motorcyclist was very short (less than 1 s), and the assumption was verified by the lateral camera recordings, which

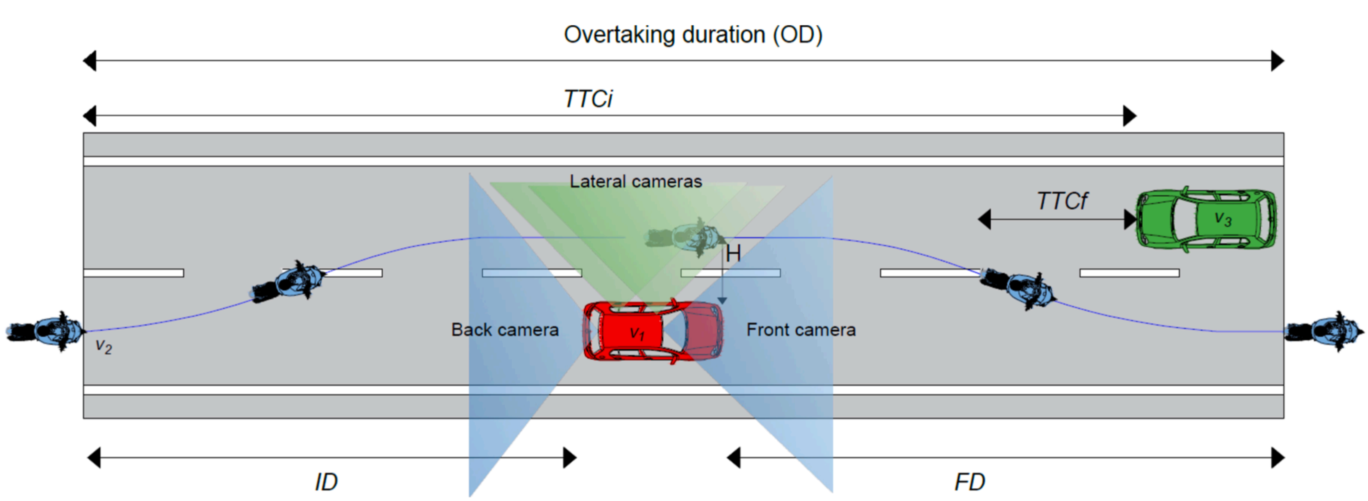

Fig. 1. Overtaking maneuver and cameras installed on the test vehicle.

confirmed that the motorcycle's position remained unchanged between the instant it was alongside the vehicle and the instant it was visible from the front camera.

Furthermore, the methodology described in Section 2.3 was used to estimate the lateral position of the test vehicle at the instant when H was determined, to assess its potential influence on rider behavior. The analysis revealed an average lateral position of the test vehicle's left wheel relative to the center of the lane of 0.86 ± 0.11 m. These results suggest that, although the lateral position of the test vehicle can theoretically influence rider behavior, the variation in this study is sufficiently low to consider its effect negligible.

To describe the riders' overtaking maneuver and to model *OD* and *H*, further variables, considered as potential predictors of the two road risk indicators (Asaithambi and Shravani, 2017; Bella and Gulisano, 2020; Guo et al., 2020; Ibrahim et al., 2018; Keshari et al., 2024; Vlahogianni, 2014), were also considered in the study.

The variable *Invasion* indicates if the rider invaded the opposite lane during the overtaking (*Invasion* = *1*) or if the overtaking occurred in the right lane (*Invasion* = *0*). The variable *Forced* gives information about the ending conditions of the maneuver. The overtaking was "forced" when a vehicle in the opposite lane induced the motorcyclist to return to the right lane (*Forced* = *1*). Otherwise, it was "voluntary" (*Forced* = *0*). The "*Invasion*" and "*Forced*" variables were assessed by the researchers through observation of the video recordings of the overtaking maneuvers.

At the beginning of the overtaking, the *Speed difference (dv)* between the motorcycle and the front vehicle is a crucial variable. In addition, the longitudinal spacing between the motorcycle and the front vehicle was defined as the *Initial longitudinal distance* (*ID*). At the same instant, the *Initial Time-To-Collision* (*TTCi*) was defined as the time required for the motorcycle and the front vehicle to collide if they carry on driving at their current speeds until the moment of the crash.

Similarly, at the end of phase 2, the *Final Time-To-Collision* (TTC_f) between the motorcycle and the oncoming vehicle was calculated.

At the end of the overtaking, the longitudinal spacing between the passing vehicle and the motorcycle was defined as *Final longitudinal distance* (*FD*).

Lastly, during the entire overtaking maneuver, the *instrumented vehicle's speed* (v_1) was recorded by a GPS. On the other hand, a tailored procedure (see Section 2.3) was employed to obtain the *motorcycle's speed* (v_2) and the *oncoming vehicle's speed* (v_3).

Table 1 shows a detailed list of all the variables of interest, while Fig. 1 presents their schematic illustration.

2.3. Data processing

The data processing consisted of a series of procedures to obtain all the variables of interest (Table 1). After the data collection phase, the software Dashware was used to synchronize the video recorded by the cameras with the speed of the instrumented vehicle (GPS data). Once synchronization was completed, another software, Kinovea, was used to select specific parts of the video (i.e., overtaking events) and to extract frames at predetermined time intervals. In this research, frames every 0.5 s were extracted to analyze the overtaking maneuver, in line with previous video-based trajectory extraction methods reported in the literature (Vlahogianni, 2014).

The dichotomous variables reported in Table 1 (*Invasion* and *Forced*) were determined by observing the overtaking events as recorded by the lateral cameras.

An ad-hoc digital image processing algorithm was instead used for the estimation of the remaining variables. The algorithm is based on the work of Psarianos et al. (2001) and later modified by (Elefteriadou and Soria, 2011) and permits to estimate the lateral position of the motorcycle and the longitudinal distance between the motorcycle and the instrumented vehicle (Fig. 2). In a previous study (Bella and Gulisano, 2020) the accuracy of the algorithm was assessed using the mean absolute percentage error (MAPE), resulting in a value of 3.51 % for longitudinal distances up to 25 m. This demonstrated that the accuracy of the method was fully consistent with the objectives of this study.

Fig. 2 shows a schematic illustration of the image acquisition geometryFig. 2 and an example of the digital image.

Any lateral (D) or longitudinal (Z) distance can be obtained from the geometry of the images, by using the following Eq. (1) and (2):

$$D = \frac{K_0 d}{h_d - h_F} \quad (1)$$

$$Z = \frac{c Y_0}{h_d - h_F} \quad (2)$$

where c is a camera calibration constant; K_0 is the camera height above ground level; *d* is the lateral distance measured in the image, h_d is the image coordinate of the point *d* and h_f is the coordinate of the vanishing point of the image.

For each frame during the overtaking event, the identification of the vanishing point and the measurement of the different parameters in Eqs. (1) and (2) allowed the estimation of all the variables of interest listed in Table 1. The lateral position of the motorcycles during the entire overtaking maneuver was determined using Eq. (1), which enabled us to determine the trajectory of the motorcycle and subsequently identify the beginning and end points of the overtaking maneuver as well as the start and end times of the maneuver. The differences between these times provided the overtaking durations (OD). The lateral clearance (H) was determined using Eq. (1) at the moment when the motorcycle was visible in the video recorded by the front camera. The initial longitudinal distance (ID) and final longitudinal distance (FD) were calculated using Eq. (2).

The speeds of the motorcycle (v_2) and the oncoming vehicle (v_3) were calculated through the speed of the instrumented vehicle (v_1, provided by GPS device) and the inter-vehicular distance (*Z*) in two consecutive instants (*t*-1 and *t*), with the following Eq. (3) (Elefteriadou and Soria, 2011):

$$v_2 = \frac{v_1(t-1) + v_2(t)}{2} + \frac{Z(t) - Z(t-1)}{\Delta t} \quad (3)$$

The variable *dv* was calculated as *v2 – v1*. Time To Collision (*TTC*) represents the remaining time between two consecutive vehicles until a collision occurs if no evasive action is taken. Therefore, the estimation of the longitudinal distance between the motorcycle and the oncoming vehicle at the beginning and end of the overtaking, divided by the speed difference, allows the calculation of TTC_i and TTC_f.

The application of the algorithm requires the preliminary detection of the vanishing point in any frame of the video. The vanishing point is the farthest point where parallel lines in 3D real-world space converge after being projected to a 2D image plane (Choi et al., 2019). Although some recent research used deep learning approach (Chang et al., 2018; Choi et al., 2019; Shuai et al., 2017), most of the existing literature

Table 1
Variables of the overtaking maneuver.

Variable	Description	Unit
OD	Overtaking duration	s
H	Lateral clearance	m
v_1	Instrumented vehicle's speed	km/h
v_2	Motorcycle's speed	km/h
v_3	Oncoming vehicle's speed	km/h
dv	Speed difference	km/h
ID	Initial longitudinal distance	m
TTC_i	Initial Time-To-Collision	s
TTC_f	Final Time-To-Collision	s
FD	Final longitudinal distance	m
Invasion	1: Yes; 0: No	
Forced	1: Yes; 0: No	

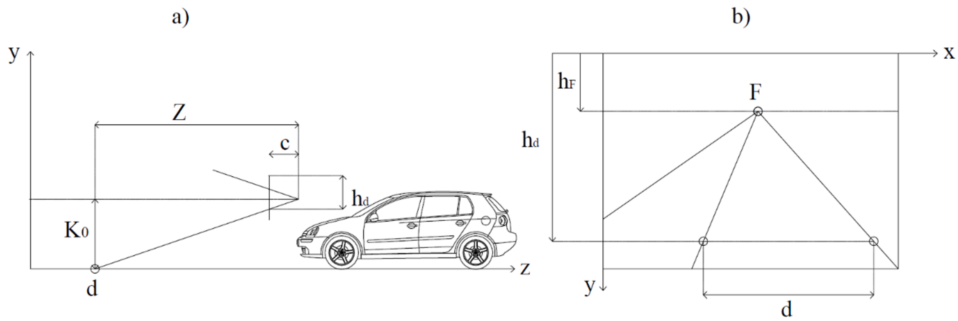

Fig. 2. Image acquisition geometry (a) and digital image (b).

estimated the vanishing point by finding the convergence points of parallel lines (Huang et al., 2017; Moon et al., 2018), which is the approach used in the present research.

The edges of the image were first detected with the Canny's operator (Canny, 1986), as shown in Fig. 3. Hough transform (Duda and Hart, 1972) was then used to determine the straight lines in the image, consisting of the line-markings and the barrier lines.

Once obtained the straight lines, they were extended, and their intersection would be the vanishing point. However, in practice, it was impossible to find a unique vanishing point. DBSCAN algorithm (Ester et al., 1996) was then utilized to find the cluster with the most vanishing point candidates, and then the gravity center of such cluster was regarded as the vanishing point. The result of the vanishing point detection is shown in Fig. 3.

The detailed theoretical approach and the verification of the reliability of this methodology can be found in Bella and Gulisano (2020).

Using the described methodology, a total amount of 139 overtaking maneuvers were recorded and analyzed in the present research. The analysis of the video recorded by the lateral cameras revealed that most of the overtaking (91 %) maneuvers were performed by invading the opposite lane, and in 25 % of the events the riders were forced to return to the opposite lane. The descriptive statistics of the collected variables are shown in Table 2.

2.4. Data analysis

Data analysis was conducted to model the overtaking duration and the lateral clearance. On the one hand, the duration of the overtaking maneuver (*OD*) was modeled with survival analysis. On the other hand, logistic regression analysis was performed to evaluate the probability of the riders adopting critical lateral clearance (H_{cr}) during the overtaking.

2.4.1. Hazard-based duration model

The use of hazard-based duration models has attracted the attention of several researchers in the field of transportation in recent years. This kind of statistical tool is believed to be the most appropriate for the analysis of duration variables, such as the reaction times of drivers and pedestrians distracted by mobile phones (Haque and Washington, 2015; Liu et al., 2021a), the driver's speed reduction times in pedestrian and cyclist crossings (Bella and Silvestri, 2016) or the drivers' overtaking duration (Moll et al., 2021; Vlahogianni, 2013). Furthermore, hazard-based duration models were used for motorcycles' safety issues, such as the time between motorcyclists' initial training and their first crash (Balusu et al., 2020) or the factors affecting motorcyclists' behavior in car-following conditions (Gulisano and Bella, 2021).

Table 2
Descriptive statistics of the overtaking events.

Variable	Description	Unit	N	Mean	St.Dev.
OD	Overtaking duration	s	139	4.6	1.7
H	Lateral clearance	m	139	1.87	0.5
v_1	Instrumented vehicle's speed	km/h	139	48.0	7.8
v_2	Motorcycle's speed	km/h	139	66.0	11.0
v_3	Oncoming vehicle's speed	km/h	35	73.0	28.7
dv	Speed difference	km/h	139	19.2	10.0
ID	Initial longitudinal distance	m	139	11.3	8.4
TTC_i	Initial Time-To-Collision	s	139	3.9	3.7
TTC_f	Final Time-To-Collision	s	35	1.7	1.9
FD	Final longitudinal distance	m	139	18.8	7.3
Invasion	Yes: 126 (91 %); No: 13 (9 %)				
Forced	Yes: 35 (25 %); No: 104 (75 %)				

In the present research, the overtaking duration (*OD*) was the duration variable. The survival function $S(t)$ is defined as the probability that an overtaking maneuver lasts more than a certain time t, and is given by Eq. (4):

$$S(t) = P(OD \geq t) = 1 - F(t) \tag{4}$$

Where $F(t)$ is the cumulative probability, ranging between 0 and 1. The hazard function $h(t)$ is a conditional probability density function (ranging between 0 and 1), representing the probability that the overtaking will end between time t and Δt, given that the event has not ended by time t (Eq. (5)):

$$h(t) = \lim_{\Delta t \to o} \frac{P(t \leq OD < t + \Delta t | OD \geq t)}{\Delta t} \tag{5}$$

Fig. 3. Canny edge detection (left) and output of vanishing point detection (right).

The accelerated Failure Time (AFT) model was applied in this research. Compared with Proportional Hazard (PH) models, in which the covariates act multiplicatively on some underlying hazard function, in AFT models the covariates rescale time directly in a baseline survivor function which is the survivor function where all covariates are zero (Hensher and Mannering, 1994). The AFT model was selected as it allows a simpler interpretation of the results as the estimated parameters quantify the corresponding effect of a covariate on the mean survival time (Ali et al., 2019; Haque and Washington, 2015, 2014).

In the AFT model, the natural logarithm of the survival time, T, is expressed as a linear function of covariates (Haque and Washington, 2015) (Eq. (6)):

$$\ln(T) = \beta X + \varepsilon \tag{6}$$

where X is a vector of explanatory variables x_i, β is a vector of estimable parameters, and ε is the error term.

Assuming that the covariates act in the form of exp(βX), the AFT model can be written as (Eq. (7) and (8)):

$$S(t|X) = S_0[t \bullet exp(\beta X)] \tag{7}$$

$$h(t|X) = h_0[t \bullet exp(\beta X)]exp(\beta X) \tag{8}$$

where S_0 and h_0 are the baseline survival and the baseline hazard function, respectively.

The development of AFT hazard-based duration models requires the assumption of a specific distributional form of the duration variable. Based on the result of previous works (Bella and Gulisano, 2020; Maji et al., 2023; Vlahogianni, 2013), log-logistic distribution was the most appropriate for modeling the overtaking duration (*OD*). However, the performance of different distributional forms was tested in this research to optimize the model.

The hazard function of the Log-logistic distribution is expressed as (Eq. (9)):

$$h_l(t) = \frac{exp(-\beta X)^{\frac{1}{\gamma}} \bullet t^{\frac{1}{\gamma - 1}}}{\gamma(1 + [exp(-\beta X) \bullet t]^{\frac{1}{\gamma}})} \tag{9}$$

While the survival function (Eq. (10)):

$$S_l(t) = \frac{1}{1 + [exp(-\beta X) \bullet t]^{\frac{1}{\gamma}}} \tag{10}$$

where γ is the shape parameter to be estimated from the data and defines the form of the hazard function: if $\gamma > 1$ the function is monotone decreasing, while if $0 < \gamma < 1$, the hazard function increases until a maximum (inflection point) and then decreases asymptotically to zero. The inflection point of the distribution is estimated as (Eq. (11)):

$$\tau^* = \frac{\left(\frac{1}{\gamma} - 1\right)^{\gamma}}{\lambda_l} \tag{11}$$

where λ_l is the Log-logistic location parameter (Eq. (12)):

$$\lambda_l = exp(-\beta X) = exp[-(\beta_0 + \beta_1 x_1 + \cdots)] \tag{12}$$

Different research has demonstrated the potential of including random effects in models to capture unobserved heterogeneity (Agbelie and Libnao, 2018; Rashidi and Mohammadian, 2011; Scarano et al., 2023). However, several attempts were made during the investigation to include a frailty distribution term (Gamma and Inverse-Gaussian) in the models to assess the unobserved heterogeneity, without obtaining any improvement in the model performance. For this reason, it was ultimately decided not to include random effects in the models.

The selection of the covariates to include in the *OD* model was made based on a trial-and-error method. All the potential covariates were first included, and the performance of the model was evaluated. Then, a systematic process of removal and addition of covariates was performed to select the best model.

The likelihood ratio chi-square test, LR chi2, was used to determine the overall significance of the model. Furthermore, the goodness-of-fit was assessed using the Cox–Snell residual plots (Cox and Snell, 1968).

2.4.2. Logistic regression

Logistic regression analysis was performed to model the rider's probability of overtaking the vehicle by adopting a critical lateral clearance (H_{cr}). Based on the distributional characteristics of the lateral clearance, the value of $H_{cr} = 1.4$ m, corresponding to the 20th percentile, was considered the cut-off point separating the safe and critical lateral clearance during overtaking. It should be noted that the assumption regarding the assigned value for identifying critical overtaking in the current study is more conservative than that presented in previous studies by Vlahogianni (2014) and Guo et al. (2020). In those studies, a threshold at the 10th percentile was established, corresponding to a critical value of 0.9 m (Vlahogianni, 2014) and 1.1 m (Guo et al., 2020), respectively.

It should be observed that these studies were conducted on different types of roads and traffic conditions, characterized by lower speeds than those observed in the present study. In other words, the critical value H_{cr} was conservatively assumed to be equal to the 20th percentile of the distribution of lateral clearances recorded to account for the increased risk of overtaking maneuvers in suburban settings (higher speeds) compared to those of the maneuvers investigated by Vlahogianni (2014) and Guo et al. (2020).

The binary dependent variable Y is equal to 1 when $H < H_{cr}$, and equal to 0 otherwise. According to Washington et al. (2020), the analysis aims to identify the best-fitting model describing the relationship between the binary dependent variable and a set of independent or explanatory variables.

The form of the logistic regression model, given a series of m explanatory variables, is (Eq. (13)):

$$Logit[P(Y=1)] = \log\left(\frac{P(Y=1)}{1 - P(Y=1)}\right) = \beta_0 + \sum_{i=1}^{m} \beta_i \bullet x_i \tag{13}$$

where β_0 is the intercept and β_i are the coefficients of m explanatory variables x_i. The coefficients of the model are estimated using the maximum likelihood method. The significance level was set to $\alpha = 0.05$, and the trial-and-error procedure was used to fit the model. Then, the probability that the rider adopts a critical lateral clearance is estimated by Eq. (14):

$$P(Y=1) = \frac{e^{\beta_0 + \sum_{i=1}^{m} \beta_i \bullet x_i}}{1 + e^{\beta_0 + \sum_{i=1}^{m} \beta_i \bullet x_i}} \tag{14}$$

The model in Eq. (14) allows determining the effect of each predictor on the odds of Y. More specifically, the value of exp(β_i) (odds ratio – OR) represents the multiplicative factor of the odds of Y when the independent variable x_i increases by one unit, with all other factors remaining constant. In other words, the odds ratio indicates the relative amount by which the odds of the outcome increase (OR > 1) or decrease (OR < 1) when the value of the corresponding independent variable increases by 1 unit (Washington et al., 2020).

The likelihood ratio chi-square test, LR chi^2, was used to determine the overall significance of a logistic model by contrasting the model with a model with no independent variables. The goodness-of-fit of the model was evaluated with Nagelkerke R^2 and Hosmer-Lemeshow test.

3. Results

3.1. Overtaking duration model

Table 3 shows the output of the hazard-based duration model for the motorcyclists' overtaking duration (*OD*). The goodness of fit was also evaluated using the Cox-Snell residuals plots (Fig. 4). A slight deviation between the Nelson-Aalen cumulative hazard curve and the bisector was obtained, indicating that the model properly fit the data.

The survival function *S(t)* and the hazard function *h(t)*, calculated by mean Eq. (9) and (10) at the mean values of the covariates, are shown in Fig. 5.

Among the various models that have been tested, the log-logistic AFT model was found to be the one that best fits the data. It should be noted that Vlahogianni (2013) obtained the same functional form for the total duration of the overtaking performed by four-wheeled vehicles in a driving simulator. In addition, this is also coherent with previous research on the *OD* of riders (Bella and Gulisano, 2020). The inflection points of the hazard function $h_{(t)}$, calculated at the mean values of covariates, was 5.7 s, which is slightly lower than that obtained by Bella and Gulisano (2020) equal to 8 s, where riders participated in the experiment using instrumented motorcycles. This result seems to highlight the different overtaking behaviors among riders involved in the two studies.

The result of the model shows that *OD* is affected by three variables, identified as statistically significant, the Initial Time-To-Collision (TTC_i), the Speed difference *(dv)* between the motorcycle and the front vehicle at the beginning of the overtaking, and the final longitudinal distance (*FD*) between the motorcycle and the passed vehicle at the end of the maneuver.

The impact of the covariates on *OD* can be evaluated by considering that any change of one unit in a covariate corresponds to a change of *100 (*exp*(β)-1)* percent in the expected survival time.

TTCi had a positive coefficient sign, indicating that the covariate had the effect of increasing *OD*. More specifically, an increase of 1 s in *TTCi* produced an increase in the overtaking duration of 2.0 %, because the motorcycle needs to cover a higher distance to carry out the maneuver. *TTCi* had an average value of 3.9 s, indicating that its average impact on *OD* is equal to $3.9 * 2.0 = 7.8$ %.

The speed difference *(dv)* between the motorcycle and the front vehicle at the beginning of the maneuver exhibits a negative sign. More specifically, the obtained outcome indicates that an increase of 1 km/h in *dv* produced a decrease in *OD* of 1.0 %. Given that *dv* had an average value of 19.2 km/h, its average impact on *OD* is equal to $19.2 * (-1.0) = -19.2$ %. Therefore, when the speed difference between the motorcycle and the vehicle increases, the motorcycle needs less time to complete the overtaking maneuver.

The final longitudinal distance (FD) between the overtaken vehicle and the motorcycle at the end of the maneuver increased the overtaking duration (OD). More specifically, an increase of 1 m in *FD* produced an increase in *OD* of 2 %. Most of the overtaking maneuvers analyzed in this study were "voluntary" (75 %), without vehicles in the opposite lane that induced the motorcyclist to return to the right lane. In such a situation, the obtained result highlights that the riders choose to delay the return to the right lane to end the maneuver, adopting a high gap with respect to the passed vehicle, to avoid any chance of lateral collision. For this reason, a higher final longitudinal distance (*FD*) resulted in a more prolonged overtaking maneuver. *FD* had an average value of 18.8 m, indicating that its average impact of *FD* on *OD* is equal to $18.8 * 2 = 37.6$ %.

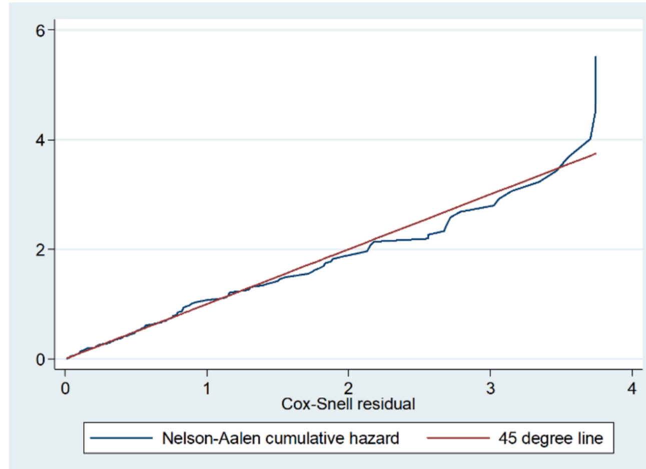

Fig. 4. Cox-Snell residuals plot.

It is interesting to observe the different orders of magnitude of the covariates in the model to understand their real effects on survival time. Considering the average values of the covariates, *FD* (final distance) had the greatest average effect (37.6 %) on the duration, followed by the variable dv (speed difference) with a negative impact of −19.2 %, while *TTCi* (initial time to collision) had a relatively minor average impact of 7.8 %.

A graphical illustration of the effects of the single covariates on the survival function of the overtaking duration, for values of the covariates equal to 15th, average value, and 85th percentile, is shown in Fig. 6.

Fig. 6 reveals that an increase in the speed difference (Fig. 6b) tended to reduce the duration of overtaking. On the contrary, a decrease in all the other covariates determined a reduction of the overtaking duration (Fig. 6a, c).

For a fixed time of 5 s, the probability that the maneuver lasts longer than 5 s could be estimated using the survival function in Eq. (10). For example, regarding the variable *dv*, if $dv = 10.3$ km/h (15th percentile) the probability that the maneuver lasts longer than 5 s ($S_{10.3\ (5)}$) was 46

Table 3
Output of the hazard-based model.

Variable	β	SE	z	p-value	Exp(β)	95 % CI	
						Lower	Upper
TTC_i	0.023	0.007	3.31	< 0.001	1.02	0.009	0.036
dv	−0.012	0.003	−3.77	< 0.001	0.99	−0.019	−0.006
FD	0.025	0.004	5.89	< 0.001	1.02	0.017	0.034
cons	1.144	0.072	15.91	< 0.001	3.14	1.004	1.286
γ	0.166	0.012					
Log-likelihood at convergence	−26.86						
Log-likelihood at zero	−203.98						
LR $chi^2_{(3)}$	39.55						
Prob > chi^2	0.000						
AIC	63.73						
BIC	78.40						
No of observations	139						

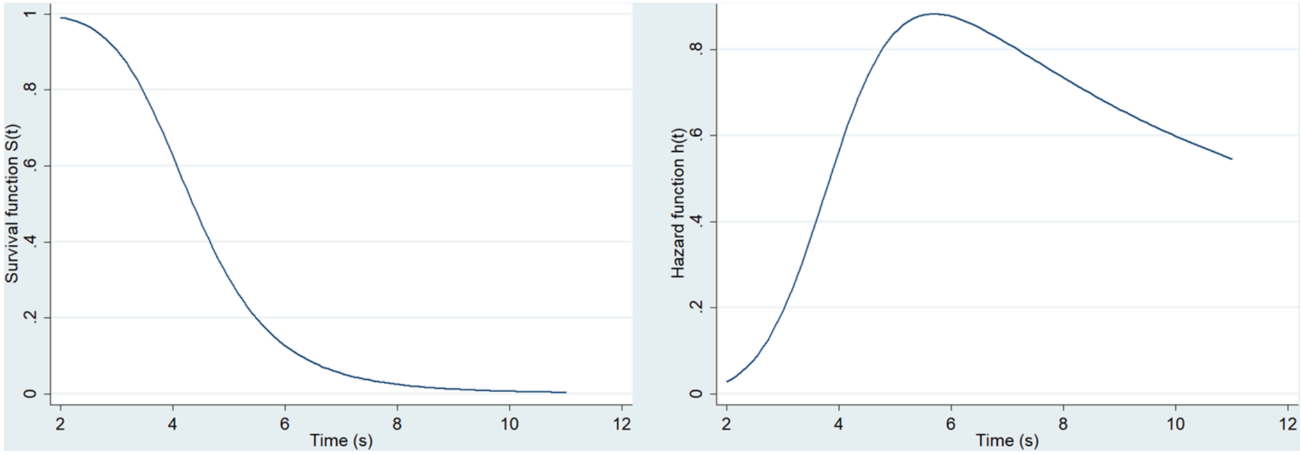

Fig. 5. Survival Function S(t) (left) and Hazard Function h(t) (right).

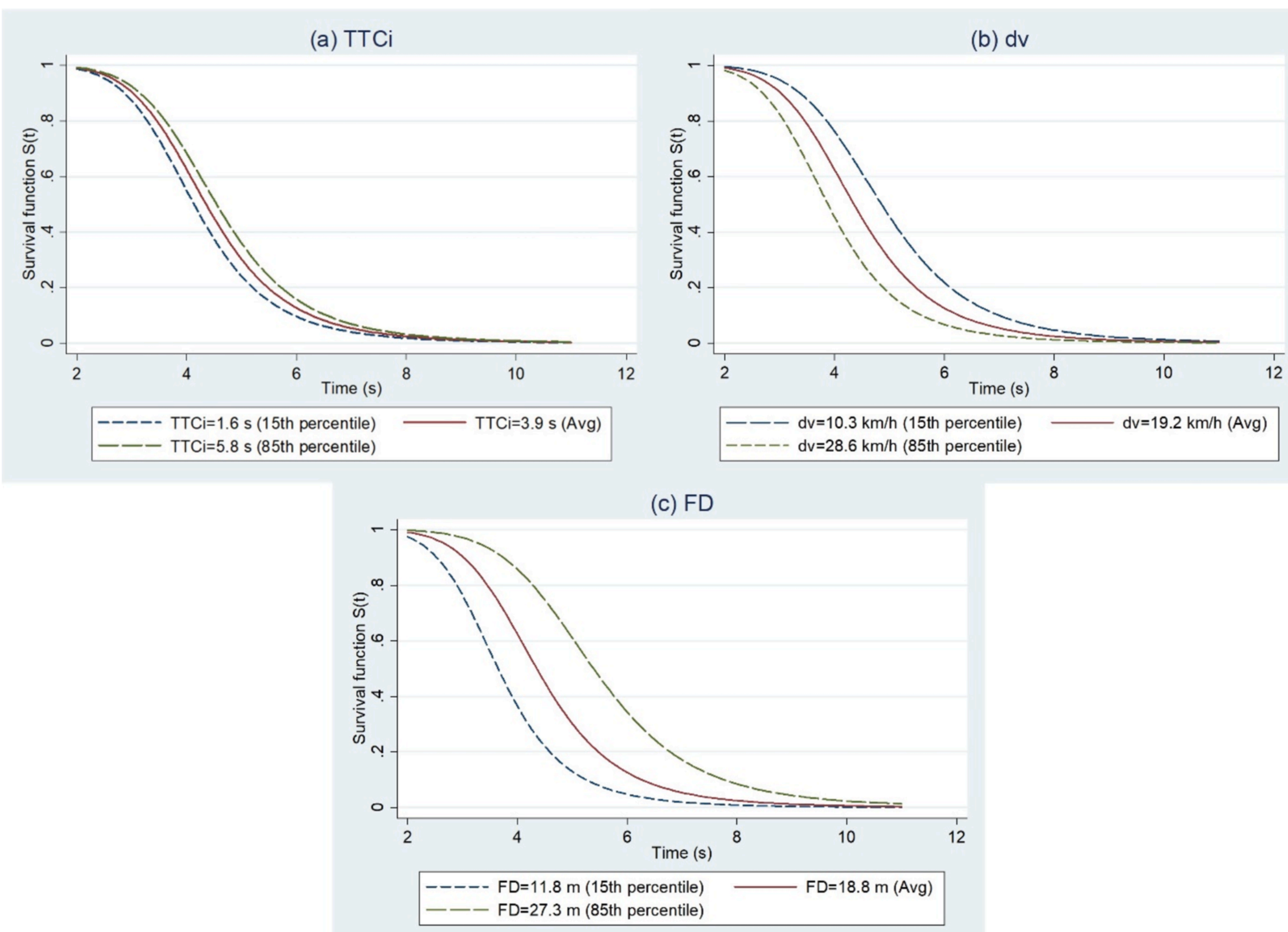

Fig. 6. Effects of the covariates on the survival function.

%, while for dv = 19.2 km/h (average value) ($S_{19.2\ (5)}$) was 30 %. By increasing the speed difference, for instance, dv = 28.6 km/h (85th percentile), the probability ($S_{28.6\ (5)}$) was reduced to 18 %. A similar approach can be employed to assess the effects on the survival function of other covariates (TTC_i and FD).

3.2. Lateral clearance model

Table 4 presents the output of the logistic model, which predicts the rider's probability of overtaking the vehicle by adopting a lateral clearance H lower than the critical H_{cr}. As previously mentioned, the binary dependent variable Y is equal to 1 when $H < H_{cr}$, and 0 otherwise. The dummy variables *Invasion* and *Forced* were defined as follows

Table 4
Output of the logistic model.

Variable	β	Odds ratio (Exp(β))	Sig.	95 % C.I. for Exp(β))	
				Lower	Upper
OD	0.333	1.395	0.009	1.085	1.793
Invasion	−2.264	0.104	0.001	0.028	0.379
Forced	1.274	3.577	0.014	1.297	9.867
Intercept	−1.412	0.244	0.087	0.048	1.229
No of observations = 139					
LR $chi^2_{(3)} = 20.86$					
Prob > $chi^2 = 0.0001$					
Nagelkerke $R^2 = 0.220$					
Hosmer-Lemeshow $chi^2_{(8)} = 5.47$; p-value = 0.701					

(see also Table 1): *Invasion* = 1 when the motorcycle invaded the opposite lane, otherwise *Invasion = 0*; *Forced* = 1 when a vehicle in the opposite lane induced the motorcyclist to return to the right lane, otherwise *Forced = 0.*

The likelihood ratio chi-square statistic was equal to LR $chi^2_{(3)} = 20.86$, and the p-value = 0.0001, ensuring the overall significance of the model. Nagelkerke R^2 was equal to 0.220, which provides acceptable goodness-of-fit. In addition, the Hosmer-Lemeshow test was not significant, $chi^2_{(8)} = 5.47$; p-value = 0.701, which guarantees that the model adequately fits the data.

The following equation (Eq. (15)) reports the obtained logistic regression model:

$$Logit[P(Y=1)] = 0.333 \bullet \mathrm{OD} - 2.264 \bullet Invasion + 1.274 \bullet Forced - 1.412 \quad (15)$$

According to the model, the likelihood of $H < H_{cr}$ depends on three variables, overtaking duration (*OD*), *Invasion,* and *Forced.* The signs of the coefficients of the independent variables indicate that the logit of adopting a lateral clearance less than H_{cr} increases as the overtaking duration (OD) increases, increases as the variable *Invasion* decreases (i.e., when the rider does not invade the opposite lane during overtaking), and increases as the variable *Forced* increases (i.e., when a vehicle in the opposite lane induces the motorcyclist to return to the right lane).

More specifically, for each increase of 1 s in the overtaking duration, the odds for a critical lateral clearance increased by a factor of 1.395. This suggests that when the time needed for the overtaking maneuver is high, the rider prefers to adopt a lower clearance, increasing the risk of a lateral collision and avoiding exposure for a long time to the more severe risk of a frontal collision with a possible oncoming vehicle. In other terms, the rider seems to experience a different risk perception connected to the two possible crash types during overtaking, i.e., a frontal collision with the oncoming vehicle and a lateral collision with the passed vehicle.

If the rider invaded the opposite lane, the odds for a critical lateral clearance decreased by 0.104 times. This result can be easily explained by the fact that the rider occupies the opposite lane precisely to overtake the vehicle with a sufficient lateral gap, avoiding any risk of a lateral collision.

Finally, if a vehicle in the opposite lane induced the motorcyclist to return to the right lane, the odds for a critical lateral clearance increased by a factor of 3.577. As previously reported, riders who perform the overtaking in the presence of opposite vehicles tend to reduce the risk of a frontal collision by reducing the lateral clearance. However, in this way, the risk of lateral collision increases.

It's interesting to note that the odds ratio values for the independent variables reveal that the variable *Invasion* has the strongest influence (OR = 0.104), followed by *Forced* (OR = 3.577), and *OD* (OR = 1.395).

The combined effects of all the variables (*OD, Invasion, and Force*) on the logit of critical clearance can be observed in Fig. 7. Fig. 7 represents the probability that the rider adopts a lateral clearance less than H_{cr}, P(Y = 1), as a function of the overtaking duration.

As shown in Fig. 7, increasing the value of *OD* increases the likelihood of adopting a lateral clearance less than H_{cr} for each combination of the other variables *Invasion* and *Forced.* For any value of OD, the likelihood of critical lateral clearance is higher when the rider does not invade the opposite lane (*Invasion* = 0) and is forced to return to the right lane (*Forced* = 1). As an example, for *OD* = 5 s, *P(Y = 1)* is equal to: (i) 0.8 for *Invasion* = 0 and *Forced* = 1; (ii) 0.55 for *Invasion* = 0 and *Forced* = 0; (iii) 0.3 for *Invasion* = 1 and *Forced* = 1; (iv) 0.1 for *Invasion* = 1 and *Forced* = 0.

4. Discussion

The descriptive statistics of the overtaking events (Table 2) show that the overtaking duration had a mean value of 4.6 s, which is lower than the value obtained in previous research (6.6 s), carried out using instrumented motorcycles (Bella and Gulisano, 2020). This is due to the higher speed adopted by the motorcycles in the present study (66.0 km/h vs 56.2 km/h that was recorded in the previous research) and the higher speed difference between the motorcycle and the passed vehicle at the beginning of the maneuver (19.2 km/h vs 9.3 km/h). Considering that the distribution of different engine sizes of the motorcycles used in the previous research and that of motorcycles recorded in the present study (estimated through observation of the video recordings) were similar, the disparities in overtaking duration and motorcycle speed are reasonably attributed to the different data collection methods (instrumented motorcycles vs. car moving method). In other words, it is believed that the awareness of being involved in an experiment induced riders participating in the previous study to adopt a more cautious driving style. However, it should be noted that such a result could also be influenced by differences in the compositions of the samples of riders (age and gender) involved in the two studies. The previous study included 20 male motorcyclists aged between 22 and 27 years old, whereas in the present study, this information could not be estimated from the observation of the videos.

It is worth noting that the obtained mean value of OD (4.6 s) aligns with findings from Keshari et al. (2024) on a two-lane undivided road section, using instrumented motorcycles. In their study, they reported a mean overtaking duration of 5.2 s for overtaking with lane sharing (the overtaking occurred in the same lane) and 5.4 s for overtaking with lane changing (the maneuver involved a lane change). Additionally, it should be emphasized that the obtained mean overtaking duration is lower than the value of 7.5 s reported by Asaithambi and Shravani (2017) who employed a moving car method for overtaking performed by motorcyclists on a two-lane road in mixed traffic conditions.

Furthermore, the obtained mean overtaking duration for motorcycles is lower than those reported for overtaking maneuvers performed by car drivers. Vlahogianni, (2013), in a driving simulation study, found a mean value of 5.5 s, while Farah (2013), in an experiment using a driving simulator, recorded a mean value of 7.1 s. Finally, Maji et al. (2023), employing an instrumented passenger car on a two-lane undivided road, found a mean value of overtaking duration equal to 9.9 s.

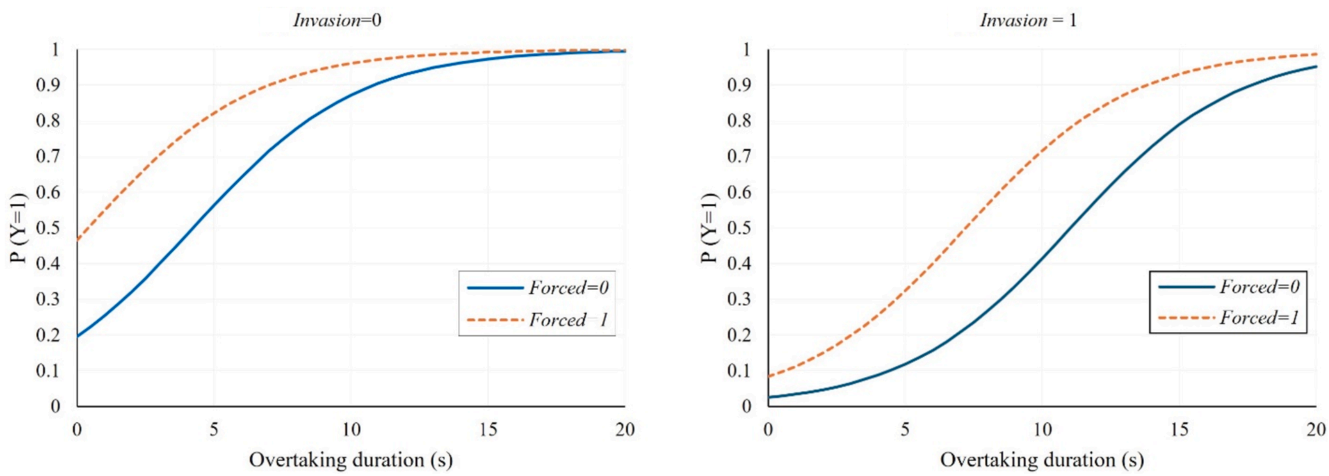

Fig. 7. Effect of the covariates on the probability of a critical lateral clearance.

This result underscores the difference in driving styles between motorcyclists and car drivers, likely attributed to the high maneuverability of motorcycles, determined by their small size and powerful engines (Vlahogianni et al., 2012).

The lateral clearance *H* had a mean value of 1.87 m. The value is higher when compared to those obtained by Vlahogianni (2014) (1.31 m) on a highly trafficked urban arterial with two lanes per direction of travel and in a constrained but moving traffic flow. This difference is reasonably attributed to the distinct types of roads and traffic conditions investigated in the two studies, particularly the fact that at lower speeds, riders tend to perceive a risk that induces them to adopt a smaller lateral distance.

The obtained mean value of lateral clearance is also higher than that recorded by Guo et al. (2020). They measured the average lateral distance as the distance between the bounding boxes of involved vehicles in the overtaking maneuver (passing two-wheelers and passed passenger cars) and recorded a mean value for e-scooters equal to 1.56 m (with a range from 0.33 m to 2.49 m). However, it's crucial to note that this result was obtained under very different conditions in terms of roads and traffic (a major street with three lanes per direction with the outside lane dedicated to two-wheelers, while the inside lanes were designed for cars) and recorded illegal overtaking maneuvers of two-wheelers that invaded the lanes designated for passenger cars. This makes a reasonable comparison with the results obtained in the present study challenging.

It is interesting to observe that at the beginning of the overtaking, riders had an average longitudinal distance (*ID*) of 11.3 m. This value is slightly lower than those obtained by Llorca and García, (2011) for the four-wheel vehicles (13 m), maybe due to the better maneuverability of the motorcycles, which allows the riders to get closer to the front vehicle and perform evasive maneuvers to prevent rear-end collision.

Regarding the results of the overtaking duration model, it is interesting to note that the inflection points of the hazard function $h_{(t)}$, calculated at the mean values of covariates, was 5.7 s (Fig. 5), which is slightly lower than that obtained by Bella and Gulisano (2020) equal to 8 s, where riders participated in the experiment using instrumented motorcycles. This result seems to highlight the different overtaking behaviors among riders involved in the two studies, as discussed above.

It should also be noted that the predictors of OD (Initial Time-To-Collision – TTC_i, the Speed difference – *dv,* and the final longitudinal distance – *FD*) are largely coincident with those obtained by (Bella and Gulisano, 2020), who found that the overtaking duration depends on the speed difference, final distance, initial distance, and initial lateral distance, as well as the type of overtaking (single or multiple overtaking).

Specifically, results consistent with those in the literature were obtained for the variables speed difference and final longitudinal distance. The speed difference (*dv*) had a negative coefficient, such that an increase of 1 km/h in *dv* resulted in a 1.0 % decrease in overtaking duration (*OD*). Similarly, Keshari et al. (2024) found that both the initial speeds of the motorcycles and the overtaken vehicles affected the overtaking duration, with the former having a negative sign and the latter having a positive sign. The same result was obtained in the previous research (Bella and Gulisano, 2020), in which the speed difference influenced the overtaking duration in the same way (an increase of 1 km/ h in the speed difference produced a reduction of the overtaking duration of 2 %).

An increase of 1 m in the final longitudinal distance (*FD*) produced an increase in *OD* of 2 %. Similar results were obtained in the previous research (Bella and Gulisano, 2020), where an increase of 1 m in the final distance tended to increase the overtaking duration by 1 %. In addition, this result is consistent with those obtained by Keshari et al. (2024), which found an increase equal to 2.6 % (for overtaking with lane changing) and 3.7 % (for overtaking with lane sharing), for each increase of 1 m of *FD*.

5. Conclusions

The paper aimed to investigate the overtaking behavior of motorcyclists in a suburban environment by modeling the overtaking duration and identifying the factors affecting it. Additionally, the study aimed to determine the likelihood of a rider overtaking a vehicle while adopting a critical lateral clearance. Riding data were collected using a passenger car instrumented with cameras and a GPS device, which recorded video s of motorcyclists performing maneuvers to overtake it. This moving car method allowed for the capture of the natural behavior of motorcyclists, avoiding the potential limitations inherent in previous instrumented motorcycle studies, such as participants being aware of their involvement in the experimentation process, and facilitated a better interpretation of the overtaking maneuvers of motorcyclists.

Subsequently, a methodology based on a digital image processing algorithm and GPS analysis was employed to characterize the 139 recorded maneuvers. Finally, survival and logistic analyses were conducted to model the duration of overtaking and lateral clearance, respectively.

The main results of the study can be summarized as follows.

The overtaking duration had a mean value of 4.6 s, consistent with the limited values reported in the literature (Keshari et al. 2024) under conditions similar to those investigated in the present study. However, it was lower than the value (6.6 s) obtained in a previous study on the same two-lane rural suburban road in Rome. This result may be attributed to the lower speeds maintained by motorcyclists in the previous study, likely influenced by the awareness of the experiment, leading them to adopt a more cautious driving style. It is important to note that the sample of riders whose behaviors were recorded in this study was not known, and the differences in overtaking duration observed could also be influenced by the potentially different composition of the rider sample compared to the participants in the previous study (20 male motorcyclists aged between 22 and 27 years old).

The hazard-based duration model highlighted that the motorcyclists' overtaking duration is influenced by three variables: the Initial Time-To-Collision (TTC_i) between the motorcycle and the front vehicle at the beginning of the overtaking, the speed difference *(dv)* between the motorcycle and the front vehicle at the same instant, and the final longitudinal distance (*FD*) between the motorcycle and the passed vehicle at the end of the maneuver. Specifically, *FD* had the greater average impact on the duration, followed by the variable *dv,* while TTC_i had a minor average impact.

Concerning the lateral clearance, a mean value of 1.87 m was found, which was lower than those reported in the literature. However, it's important to underline that the literature values are referenced to different types of roads and traffic conditions compared to those investigated in the present study.

The logistic regression analysis revealed that the probability of overtaking the vehicle by adopting a lateral clearance lower than the critical one depends on three variables: overtaking duration (*OD*), *Invasion,* and *Forced*. Specifically, the logit of critical lateral clearance increases as the overtaking duration increases, when the rider does not invade the opposite lane during the overtaking, and when a vehicle in the opposite lane induces the motorcyclist to return to the right lane. The values of the odds ratio for the three independent variables showed that the variable *Invasion* had the strongest influence, followed by *Forced* and overtaking duration.

Some limitations of the study should be recognized.

The main limitation of this study is identified in relation to the limited number of overtaking maneuvers where the rider did not invade the opposite lane (only 13 events, 9 % of the total maneuvers) and was forced to return to the right lane by an oncoming vehicle (35 maneuvers, 25 %). Therefore, further research efforts should be aimed at expanding the sample of overtaking maneuvers, especially those analyzed in limited numbers in this study.

Further potential limitations arise from the inability to accurately determine the position of the test vehicle on the cross-section during the entire overtaking maneuver and from the influence of the vehicle's oscillation and the installed cameras on the determination of the vanishing point, and consequently, on the parameters obtained using the proposed digital image processing algorithm.

Regarding the first limitation, the lateral position of the test vehicle was estimated only at the moment when H was determined. The variation in lateral position was minimal and should not significantly affect rider behavior. However, future research should ensure a consistent vehicle position on the cross-section throughout the entire overtaking maneuver.

Regarding the second potential limitation (vehicle oscillation and thus the oscillation of the attached cameras), although the test vehicle maintained a limited speed that did not cause significant oscillations of the installed cameras, further research should assess the potential impact of camera oscillation on the parameters derived from the proposed digital image processing algorithm.

Moreover, although the accuracy of the algorithm was confirmed in a previous study and is considered fully consistent with the objectives of this study, it should be further validated through comparisons with alternative methods and by assessing its applicability to different road geometries, such as curves and varying longitudinal grades.

Finally, the impact of other factors, such as the age and gender of the riders, traffic density, and pavement conditions, should be assessed.

Despite the recognized limitations, this research is believed to provide valuable contributions to understanding motorcyclist behavior during overtaking maneuvers and to the development of more realistic microsimulation models that account for the actual behavior of riders. This enhances the accuracy and reliability of these models, particularly for different suburban traffic flow conditions and safety scenarios. More specifically, rider behavior, in terms of overtaking duration (OD) or lateral clearance (H), can be simulated using the probabilistic models obtained in the present study, instead of relying on fixed deterministic values.

Additionally, the proposed models can contribute to the development of Advanced Rider Assistance Systems (ARAS) based on connected vehicle technologies (vehicle-to-vehicle, vehicle-to-infrastructure) aimed at supporting motorcyclists to make appropriate choices to avoid significant risks of incidents caused by the complex overtaking maneuver. During an overtaking maneuver, an instrumented motorcycle equipped with an ARAS system configured to evaluate Overtaking Duration (OD) and Lateral Clearance (H) using the defined models could provide valuable feedback to riders, helping them adopt safer behaviors and avoid collision risks. Insights from this research can aid also in the next generation of designing road infrastructure that better accommodates motorcyclists' needs, potentially reducing accident rates.

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CRediT authorship contribution statement

Francesco Bella: Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Supervision, Funding acquisition. **Federico Gulisano:** Investigation, Software, Data curation, Formal analysis, Writing – original draft. **Valerio Gagliardi:** Methodology, Investigation, Software, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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