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# Road safety of passing maneuvers: a bivariate extreme value theory approach under non-stationary conditions

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## 1 Abstract

Observed accidents have been the main resource for road safety analysis over the past decades. Although such reliance seems quite straightforward, the rare nature of these events has made safety difficult to assess, especially for new and innovative traffic treatments. Surrogate measures of safety have allowed to step away from traditional safety performance functions and analyze safety performance without relying on accident records. In recent years, the use of extreme value theory (EV) models in combination with surrogate safety measures to estimate accident probabilities has gained popularity within the safety community.

In this paper we extend existing efforts on EV for accident probability estimation for two dependent surrogate measures. Using detailed trajectory data from a driving simulator, we model the joint probability of head-on and rear-end collisions in passing maneuvers. We apply the Block Maxima method and estimate several extremal univariate and bivariate models, including the logistic copula. In our estimation we account for driver specific characteristics and road infrastructure variables. We show that accounting for these factors improve the head-on and rear-end collision probabilities estimation. This work highlights the importance of considering driver and road heterogeneity in evaluating related safety events, of relevance to interventions both for in-vehicle and infrastructure-based solutions. Such features are essential to keep up with the expectations from surrogate safety measures for the integrated analysis of accident phenomena, which show to significantly improve from the best known stationary extreme value models.

## 2 Keywords

Road safety; Small probability estimation; Block Maxima; Multivariate EV distribution; Passing maneuvers; Non-stationary model

## 1    **2    Introduction**

### 2    **2.1    Motivation**

3    Prediction of accidents has been a major topic in traffic safety for the last couple of decades. Despite the huge  
4    efforts that researchers have put in developing accident prediction models (Bonneson, 2010), there is a great  
5    tendency in the last decades to develop new proactive methods for safety evaluation that are not based on accident  
6    records (Archer, 2004; Kraay & Van der Horst, 1985). Evaluating conflicts and risky situations between road users  
7    has been the main alternative and multiple methodologies can be found in the literature: the Swedish traffic conflict  
8    technique (Hydén, 1987), DOCTOR method (Kraay & Van der Horst, 1985), and the use of surrogate safety  
9    measures (Archer, 2004). The main challenge is the link between these measures and the number of accidents.  
10    Zheng, Ismail, and Meng (2014) indicate that the validity of surrogate safety measures is usually determined by  
11    its correlation with accident frequency which is usually assessed using regression analysis. However, regression  
12    analysis still incorporates accident counts which are known to suffer from underreporting and quality issues, and  
13    thus this approach is limited. Besides, it is difficult to insure the stability of the accident-to-surrogate ratio, and  
14    this relationship also hardly reflects the physical nature of accident occurrence (Zheng et al., 2014). Therefore,  
15    there is a need to develop an alternative approach to predict the number of accidents based on surrogate safety  
16    measures. Songchitruksa and Tarko (2006) proposed a new and more sophisticated approach based on the Extreme  
17    Value (EV) theory to estimate the frequency of accidents based on measured accident proximity.

### 18    **2.2    Extreme Value (EV) Approach**

19    The EV approach has three considerable advantages over the traffic conflict technique: (a) it abandons the  
20    assumption of fixed ratio converting the surrogate event frequency into accident frequency; (b) accident risk given  
21    the surrogate event is estimated based on the observed variability of accident proximity without using accident  
22    data; (c) the accident proximity measure precisely defines the surrogate event.

23    The implicit assumption of the EV theory is that the stochastic behavior of the process being modeled is sufficiently  
24    smooth to enable extrapolation to unobserved levels (De Haan & Ferreira, 2006). In the context of road safety, the  
25    more observable traffic conflict events are used to predict the less frequent accidents, which are often unobservable  
26    in a short time period (Zheng et al., 2014). The field of EV theory, pioneered by Fisher and Tippett (1928), is a  
27    commonly applied theory in many fields, such as in meteorology, hydrology, finance (Zheng et al., 2014) and very  
28    recently, road safety analysis Songchitruksa and Tarko (2006). Songchitruksa and Tarko (2006) used an EV  
29    approach to build up relationships between occurrences of right-angle accidents at urban intersections and

1 frequency of traffic conflicts measured by using post-encroachment time. A major improvement of the latter study  
2 is that it links the probability of accident occurrence to the frequency of conflicts estimated from observed  
3 variability of accident proximity, using a probabilistic framework and without using accident records. The generic  
4 formulation of the application of EV to road safety analysis was then proposed by Tarko (2012) and it was only  
5 very recently applied to other accident types and data sets (Jonasson & Rootzén, 2014; Zheng et al., 2014; Åsljung  
6 et al., 2017; Orsini et al., 2018; Wang et al., 2018). The formulation relies usually, but not exclusively, on time-  
7 based surrogate measures and estimates the probability of accident occurrence using the EV fitted distribution of  
8 such measures (see Appendix 1 for formulation details). These studies have relied mostly on univariate EV models,  
9 and only very recent studies have explored the use of multi(bi)-variate approaches: Jonasson and Rootzén (2014)  
10 applied the bivariate block maxima approach to study near-crashes selection bias in a naturalistic driving setting,  
11 focusing on the relationship of different surrogate measures in rear-end collisions. In a series of recent studies  
12 published during the revision of this manuscript, Zheng et al. (2018, 2019a, 2019b) explored the use of bivariate  
13 EV to combine multiple surrogate safety measures obtained from the same pair of vehicles to predict the  
14 probability of specific crash events. In Zheng et al. (2018) post encroachment time (PET) and length proportion of  
15 merging (LPM) are used in a bivariate threshold excess model to estimate collision probability in freeway merging  
16 scenario. Later, in Zheng et al. (2019a) focuses on finding the best pair of severity-specific surrogate safety  
17 measures to estimate the probability of crash at signalized intersections and validates it with actual crash data.  
18 Finally, Zheng et al. (2019b) compares univariate and bivariate GEV and GP for left turning vehicles at  
19 intersections. This application series provide a concerted evidence of higher accuracy of bivariate against  
20 univariate EV predictions.

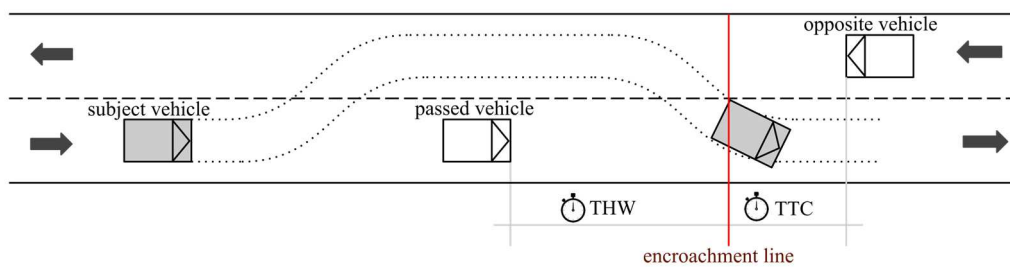
21 In this paper, we extend the EV -based road safety application state-of-the-art with the first non-stationary bivariate  
22 and copula-based EV models as a way to formalize the dependencies in events resulting from two interlinked  
23 phenomenon's and illustrate it for the context of passing maneuvers.

24

### 25 **2.3 Risk of Passing Maneuvers**

26 Passing maneuvers on two-lane roads (one lane per travel direction) carries several types of risks. The process of  
27 passing involves, synchronizing the vehicle's speed with that of the vehicle in front, estimating the available gap  
28 on the opposite direction and evaluating its suitability to successfully perform the passing maneuver, and finally  
29 return to the main driving lane while keeping a sufficient safe gap from the passed vehicle, as well as, from the

1 vehicle on the opposite direction. The gap from the passed vehicle at the end of the passing maneuver is termed in  
 2 this study as 'THW'. It reflects the time headway between the front of the passed vehicle and the rear of the passing  
 3 vehicle – a measure for rear-end and side-collisions with the passed vehicle<sup>1</sup>. The gap from the vehicle on the  
 4 opposite direction is termed in this study 'TTC' for time-to-collision between the passing and the opposite vehicle  
 5 – a measure for head-on collisions. Both of these gaps are calculated at the end of the passing maneuver. In this  
 6 study both measures will be used: the THW was calculated as the remaining distance between the passing and  
 7 passed vehicle at the end of the passing maneuver divided by the driving speed of the passed vehicle, while the  
 8 TTC was calculated as the remaining distance between the passing and opposing vehicle divided by the sum of  
 9 their speeds.



10  
 11 **Figure 1 Schematic figure of maneuver and surrogate safety measures of interest**

12  
 13 **2.4 Drivers' Characteristics**

14 Several studies have shown that there are significant differences in passing behaviors among different drivers.  
 15 Farah (2011) using a driving simulator found that gender and age have a significant impact on the passing behavior.  
 16 She found that male drivers pass more frequently than female drivers. They also maintain smaller following time  
 17 gaps from the front vehicle before initiating a passing maneuver and accept shorter gaps in the opposite traffic for

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<sup>1</sup> Note that the THW measure used in this paper is equal to the PET during a lane change maneuver between the merging subject vehicle and the following passed vehicle in the target destination lane. It is defined as the time difference between the end of the subject vehicle leaving the encroachment line and the front of the passed vehicle arriving at the encroachment line. Similarly to our case, the encroachment line is a virtual line perpendicular to the lane dividing marker and crossing the intersection point of the lane dividing marker and the lane change trajectory (Zheng et al., 2014).

1 passing. Younger drivers have significantly lower critical gaps and higher desired driving speeds compared to  
2 older drivers. They also keep smaller gaps from the front vehicle at the end of the passing maneuvers. These  
3 behaviors increase the risk of collisions. Llorca, Garcia, Moreno, and Perez-Zuriaga (2013) reached similar  
4 conclusions using an instrumented vehicle. The authors found that young male drivers have shown a more  
5 aggressive behavior when passing compared to other groups of drivers. Passing times were around 1s lower than  
6 other drivers, while average speed difference was 4 km/h higher. Farah, Polus, Bekhor, and Toledo (2007) tested  
7 the significance of including driving styles in the passing behavior model, and found that drivers who are  
8 characterized by an anxious driving style and/or patient and careful driving style have larger critical gaps.  
9 Vlahogianni and Golias (2012) emphasize that the behaviors of young male and female drivers during passing  
10 maneuvers are different and this is because of differences in the process of scanning and evaluating available  
11 opportunities for passing.

12 To summarize, the integration of drivers' characteristics and driving styles in accident prediction is valuable and  
13 have the potential to contribute to understanding accident causation. Previous EV models did not account for such  
14 factors.

### 15 **3 Research Method**

16 The aim of this study is to test two different methods to estimate accident probability in passing maneuvers. The  
17 first approach analyzes the risk of individual types of accidents during passing maneuvers, including: (1) head-on  
18 collisions using the proximity measure of the minimum TTC to the vehicle in the opposite direction; (2) rear-end  
19 collisions using the proximity measure of the minimum THW measured from the front of the passed vehicle to the  
20 rear-end of the passing vehicle. The second approach aims to analyze the joint risk of colliding with the opposite  
21 or passed vehicle during passing maneuvers using the two surrogate safety measures (THW and TTC).

#### 22 **3.1 Modeling Approach**

23 There are two families of EV distributions which follow two different approaches to sample extreme events: (1)  
24 the Generalized Extreme Value (GEV) distribution which is used in the block maxima or minima (BM) approach,  
25 in which maxima over blocks of time (or space) are considered; (2) the Generalized Pareto (GP) distribution which  
26 is used in the peaks over threshold (POT) approach (Coles, Bawa, Trenner, & Dorazio, 2001), where all values  
27 above a certain threshold are used. In this paper we focus our attention on the application of the BM approach for  
28 estimating the risk of a single type of accident (head-on or rear-end collision), while for estimating the risk of both  
29 types of collisions jointly, the bivariate distribution with copula approach was considered. We opted for the BM

1 in favor of the POT following, (a) our previous findings in terms of stability for the univariate case (Farah and  
 2 Lima Azevedo, 2016), (b) weaker consistency in results from POT trials considered at an earlier stage of this  
 3 research (c) BM favorable conditions in case of weak dependence and (d) that a detailed comparative study  
 4 between BM and POT in a multivariate setting is out of scope for the present manuscript although much needed  
 5 (Büncher and Zhou, 2018). Note that the univariate POT is well known and has been extensively discussed (De  
 6 Haan & Ferreira 2006) and the estimation process to go to the bivariate POT is much similar to the case of going  
 7 from the univariate to bivariate BM discussed below and also be found in recent applications (see for example  
 8 Zheng & Sayed 2019).

### 9 **3.2 The BM Approach**

10 Mathematically, the standard GEV function is as follows (von Mises, 1936; Zheng et al., 2014):

$$G(x) = \exp\left(-\left[1 + \xi \left(\frac{x-u}{\sigma}\right)\right]_+^{\frac{-1}{\xi}}\right) \quad (\text{Eq. 3})$$

11 Following the Block Maxima approach, the observations are aggregated into fixed intervals over time or space,  
 12 and then the extremes are extracted from each block by identifying the maxima in each single block. If  
 13  $\{X_1, X_2, \dots, X_n\}$  is a set of independently and identically distributed random observations with unknown  
 14 distribution function  $D(x) = Pr(X_i \leq x)$ , the linearly normalized maximum  $M_n = \max\{X_1, X_2, \dots, X_n\}$  will  
 15 converge to a GEV distribution when  $n \rightarrow \infty$ . Three parameters identify this distribution: the location parameter,  
 16  $-\infty < u(\mathbf{z}) < \infty$ ; the scale parameter,  $\sigma > 0$ ; and the shape parameter,  $-\infty < \xi < \infty$ . If the shape parameter,  $\xi$ ,  
 17 is positive, then this would yield the Frechet Cumulative Distribution Function (CDF) with a finite lower endpoint,  
 18  $(u - \sigma/\xi)$ , if  $\xi$  is negative, this will yield the (reversed) Weibull CDF with finite upper endpoint  $(u + \sigma/|\xi|)$ ,  
 19 and if  $\xi = 0$  this yields the Gumbel CDF. In a non-stationary BM model several factors,  $\mathbf{z}$ , can be included in the  
 20 location parameter to account for their impact on the probability of the extreme events, i.e.  $u(\mathbf{z})$ . More details on  
 21 the GEV properties can be found in (Tarko, 2012). Details on the statistical properties of EV can be found in (Coles  
 22 et al., 2001; Dombry & Ferreira, 2018), and on the theoretical background of its applicability for surrogate (road  
 23 safety analysis in (Tarko, 2012).

### 24 **3.3 Parametric Bivariate EV distributions**

25 In some applications, the study of accident probability using multivariate distributions is of interest. Traditionally,  
 26 single surrogate safety measures are used to estimate a single type of events. However, it is expected that in some  
 27 of the complex accident phenomena, multiple pre-accident events can play an important role in a potential accident.

1 Passing maneuvers are a typical case where both the opposite and passed vehicles are key stimulus during driver's  
 2 decision making. The bivariate model aims to estimate a measure of risk that not only takes into account the  
 3 possibility to collide with the opposite vehicle but also with the passed vehicle.

4 Given a bivariate random sample  $(X_1, Y_1), \dots, (X_n, Y_n)$ , much of extreme value theory is concerned with the limiting  
 5 behavior of a suitable normalization of the component wise maxima  $(M_{1,n}, M_{2,n})$ , where  $M_{1,n} = \max(X_1, \dots, X_n)$   
 6 and  $M_{2,n} = \max(Y_1, \dots, Y_n)$ . More precisely, it is assumed that there exists a non-degenerate bivariate distribution  
 7 function BG such that, as  $n \rightarrow \infty$ :

$$P \left\{ \frac{M_{1,n} - b_{1,n}}{a_{1,n}} \leq x, \frac{M_{2,n} - b_{2,n}}{a_{2,n}} \leq y \right\} \rightarrow BG(x, y) \quad (\text{Eq. 4})$$

8 for sequences  $a_{j,n} > 0, b_{j,n} \in \mathbb{R}, j = 1, 2$  (Capéraà & Fougères, 2000). To analyze separately the behavior of the  
 9 marginals and the dependence structure of the distribution, it is convenient to write

$$BG(x, y) = C\{F(x), G(y)\} \quad (\text{Eq. 5})$$

10 in terms of univariate extreme value margins F and G, and a dependence function C (Capéraà & Fougères, 2000;  
 11 De Haan & Ferreira 2006) defined for all  $0 \leq w, v \leq 1$  by:

$$C(w, v) = P\{F(X) \leq w, G(Y) \leq v\} = \exp \left[ \log(wv) A \left\{ \frac{\log(w)}{\log(wv)} \right\} \right] \quad (\text{Eq. 6})$$

12 where  $A(\cdot)$  is a convex function on  $[0, 1]$  such that  $\max(t, 1 - t) \leq A(t) \leq 1$  for all  $0 \leq t \leq 1$  (Pickands, 1981).

13 Given this representation and except for the margins, the bivariate extreme value distribution BG for component  
 14 wise maxima is characterized by a one-dimensional function  $A(\cdot)$ . Common used functions are the logistic,  
 15 asymmetric logistic, negative logistic, asymmetric negative logistic, bilogistic and negative bilogistic. These  
 16 extreme-extreme value specification for the dependence function along with common assumptions on the  
 17 distribution for both marginals (e.g. Gumbel, Exponential, Fréchet or Weibull) allow for the formulation of well-  
 18 defined parametric models. Information on the statistical properties of the estimation methods that have been  
 19 developed in the context of bivariate EV can be found in (Capéraà & Fougères, 2000; Pickands, 1981). The few  
 20 recent bivariate models found in the literature and described in Section 2 follow this approach (as, for example,  
 21 the logistic case in Zheng & Sayed, 2019b). Extending this line of research, here we estimate a large set of  
 22 stationary and non-stationary parametric EV models' using the maximum likelihood (ML) method in R (v3.0.3)  
 23 using the `exTremes` and `evd` packages (Gilleland and Katz, 2011).

24

25



### 1 **3.4 Copula-based Bivariate distributions**

2 Here, we focus our attention on the bivariate distribution with a copula method as alternative approach due to the  
3 uncertain form of dependence (not necessary linear) between the two surrogate safety measures. While in the  
4 previous section, well defined parametric bivariate EV models rely on a clear predefined structure of  $C(\cdot)$ ,  $F(\cdot)$   
5 and  $G(\cdot)$ , the Sklar's Theorem (1959) ensures that it is possible to estimate a multivariate distribution by separately  
6 estimating the marginal distributions and the copula separately. As in eq. 6, the copula  $C(\cdot)$  is a multivariate  
7 distribution whose margins  $F(\cdot)$  and  $G(\cdot)$  are all uniform over  $(0,1)$ , and can be defined as:

$$C(w, v) = P\{F(X) \leq w, G(Y) \leq v\} \quad (\text{Eq. 7})$$

8 The copula not only provides a structure for the dependence between the two variables but also reveals itself to be  
9 invariant under strictly monotone transformations. Using copulas allows to test and select different distributions  
10 for the marginals and for the copulas in a two-stage statistical procedure, thus relaxing some of the predefined  
11 assumptions needed for the parametric multivariate estimation case. In our particular overpassing event, here  
12 represented by the two interlinked phenomena's (relative trajectories of subject-passed and subject-opposite  
13 vehicles), the dependence structure of the two surrogate safety measures is unclear and the assumption of strong  
14 extremal dependence may not be valid. For surrogate safety measures computed for the same phenomenon (as in  
15 the existing literature mentioned above) the dependence function may have a clearer dependence structure as the  
16 measures come from the same vehicle trajectory pairs. The two most frequently used copula families are elliptical  
17 copulas, extreme-value copulas, Archimedean and polynomial copulas. More details on these copula families can  
18 be found in Fang, Kotz, and Ng (1990), Nelsen (2007), and Genest and Rivest (1993). To assess if a given copula  
19 is well fitted to the data under analysis, a goodness-of-fit test is performed based on statistics such as the rank-  
20 based versions of the Cramer-von Mises or the Kolmogorov-Smirnov. An example of goodness-of-fit testing  
21 overview are given in Berg (2009). In this study, all copula models' were estimated in R (v3.0.3) using the package  
22 `VineCopula` (Brechmann & Schepsmeier, 2013) and `copula` (Yan, 2007).

### 23 **3.5 Data Collection**

24 The data for this study was obtained from a driving simulator experiment developed by Farah, Bekhor, and Polus  
25 (2009) for modelling drivers' passing behavior on two-lane rural highways. In this experiment the STISIM  
26 (Rosenthal, 1999) driving simulator was used. STISIM is a fixed-base interactive driving simulator, which has a  
27 60° horizontal and 40° vertical display. The driving scene was projected onto a screen in front of the driver with a  
28 rate of 30 frames per second. A total of 16 simulator scenarios were designed in order to have a better understating

1 of how different infrastructure and traffic related factors affect drivers' passing behavior. The 16 different  
2 scenarios are the result of an experimental design that included 4 factors in 2 levels, which are: the speed of the  
3 front vehicle (60 or 80 km/h), the speed of the opposite vehicle (65 or 85 km/h), the opposite lane traffic volume  
4 (200 or 400 veh/h), and the road curve radius (300-400 or 1500-2500 m). However, all the scenarios were  
5 composed of 7.5 km of two-lane rural highway section with no intersections, and good weather conditions. Each  
6 driver drove 4 scenarios out of the 16 scenarios which were selected following a partial confounding method that  
7 was adopted (Hicks & Turner). A more detailed information about this experiment can be found in (Farah, 2013;  
8 Farah et al., 2009).

9 A total of 100 drivers (64 males and 36 females) with at least 5 years of driving experience participated in the  
10 driving simulator experiment on a voluntary base. 67 drivers are with an age between 22 and 34 years old, 20  
11 drivers with an age between 35 and 49 years old, and the remaining 12 with an age between 50 and 70 years old.  
12 Prior to participating in the driving simulator experiment each driver filled a questionnaire composed of two parts:  
13 the first part included questions on the driver personal characteristics (including questions such as: gender, age,  
14 and driving experience), while the second part included the Multidimensional Driving Style Inventory (MDSI)  
15 developed by Taubman Ben-Ari et al. (Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). The MDSI is a 6-point  
16 scale, which consists of 44 items that are used to characterize four factors that represent different driving styles:  
17 (1) *Reckless and careless driving style*, which refers to deliberate violations of safe driving norms, and the seeking  
18 of sensations and thrills while driving. It characterizes persons who drive at high speeds, race in cars, pass other  
19 cars in no-passing zones, and drive while intoxicated, probably endangering themselves and others; (2) *Anxious*  
20 *driving style*, which reflects feelings of alertness and tension as well as ineffective engagement in relaxing activities  
21 during driving; (3) *Angry and hostile driving style*, which refers to expressions of irritation, rage, and hostile  
22 attitudes and acts while driving, and reflects a tendency to act aggressively on the road, curse, blow horn, or "flash"  
23 to other drivers, and (4) *Patient and careful driving style*, which refers to planning ahead, attention, patience,  
24 politeness, and calmness while driving, as well as obedience to traffic rules. Factor scores were calculated for each  
25 respondent on each of these four driving styles.

#### 26 **4 Results and Analysis**

27 The data set from the driving simulator experiment resulted in a total of 1287 completed passing maneuvers, 9  
28 head-on collisions and 2 rear-end collisions. The detailed vehicle movement from the simulator was processed to

1 obtain the two surrogate safety measures of interest at the end of passing maneuvers: the TTC with the opposing  
2 vehicles and the THW between the passed and passing vehicles.

### 3 **4.1 Univariate Model**

4 In the univariate model, a separate distribution was fitted to the minimum TTC and THW measurements resulting  
5 from the 1287 passing maneuvers. In the GEV approach, each passing maneuver is represented by one block for  
6 which we take its minima for each of the surrogate safety measures considered. Note that accident observations  
7 were not used in the estimation procedure. GEV models pertain to continuous random variables that give zero  
8 mass to any real value, hence to zero. But accidents do happen and can be recorded with zero value with positive  
9 mass. The continuous random variables do not take such values into account and, thus, recorded accidents were  
10 not considered in the estimation dataset.

#### 11 **4.1.1 Head-on collisions**

12 Aiming at estimating the probability of a head-on collision for a single passing maneuver, the minimum TTC was  
13 considered as a head-on accident surrogate measure. The data was then filtered to account only for values smaller  
14 than 1.5s (Hydén, 1987; Jonasson & Rootzén, 2014; Vogel, 2003), leading to a total of 463 observations. Knowing  
15 that 9 maneuvers ended with actual head-on collisions, the empirical probability of a head-on collision in a passing  
16 maneuver given that a critical TTC (i.e. TTC lower than 1.5 s), is  $9/(463+9)=0.0191$ , with 95% binomial  
17 confidence interval (0.0089,0.0366). Note that different filtering conditions were also tested in estimation (see  
18 Appendix 2).

19 We start with an existing stationary BM model developed by Farah and Lima Azevedo (2016). The authors  
20 estimated that the parameters of the univariate GEV cumulative distribution function are  $\hat{\mu} = -0.993$  (0.0212),  
21  $\hat{\sigma} = 0.0383$  (0.0163) and  $\hat{\xi} = -0.236$  (0.0500). Figure 1. presents the probability density function of the  
22 empirical and modeled negated TTC (*upper left*) and the simulated QQ plot (*upper right*). This model was then  
23 upgraded by the authors to a non-stationary BM model. They concluded that the covariates '*passinggap*',  
24 '*tailgatetp*', '*speedfront*', '*curvature*' as defined below, related to the infrastructure and traffic, significantly  
25 contribute to the prediction of the probability of a head-on-collision during a passing maneuver. While the  
26 covariate '*speedpv*' was not found to be significant. Variables related to drivers' personal characteristic (gender,  
27 age, and driving style) were not tested. In this study, we will test whether drivers' personal characteristic  
28 significantly contribute to the model in addition to the traffic and road variables. The variables are defined as  
29 following:

- 1 • *passinggap*: is defined as the time gap between the opposing vehicle and the subject vehicle, at the time that
- 2 the lead vehicle encounters the subject vehicle;
- 3 • *tailgatetp*: time gap between the subject vehicle and the front vehicle at the moment of start passing (s);
- 4 • *speedfront*: speed of the front vehicle at the moment of start passing (m/s);
- 5 • *curvature*: road curvature (1/m);
- 6 • *speedpv*: speed of the passing vehicle (m/s);
- 7 • *gender*: gender of the driver (1-male; 0-female);
- 8 • *age*: categorical variable, with ranges 22-34; 35-49 and 50-70;
- 9 • *drivingstyle*: angry & hostile; anxious; reckless & careless; patient & careful (Taubman-Ben-Ari et al., 2004);

10 A driver was considered to have started the overtaking maneuver when the front left wheel crossed the centerline  
 11 and to have completed the overtaking maneuver when the rear left wheel crossed the road centerline (Farah, 2016).  
 12 A set of a non-stationary models considering different combinations of covariates were estimated. Table 1 presents  
 13 the four best non-stationary models with a range of likelihood ratio p-value between  $2.773 \times 10^{-9}$  and  $1.931 \times$   
 14  $10^{-8}$  (Model #1 to #4). The estimated likelihood ratio tests are shown in Table 2. The previously estimated non-  
 15 stationary model by Farah and Lima Azevedo (2016), presented as Model #0, is used as a benchmark for assessing  
 16 the performance of the other models.

17 **Table 1 Estimation results of the non-stationary BM approach for head-on collisions**

Non-stationary model	#0	#1	#2	#3	#4
	Est. (Std. Error)	Est. (Std. Error)	Est. (Std. Error)	Est. (Std. Error)	Est. (Std. Error)
$\hat{\mu}_0$	-1.045 (0.137)	-0.983 (0.139)	-0.927 (0.145)	-0.953 (0.145)	-1.107 (0.139)
$\hat{\mu}_1$ (speedFront)	0.024 (0.006)	0.026 (0.006)	0.027 (0.006)	0.025 (0.006)	0.027 (0.006)
$\hat{\mu}_2$ (tailgatetp)	0.002 (0.002)	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)
$\hat{\mu}_3$ (passinggap)	-0.022 (0.004)	-0.023 (0.004)	-0.023 (0.004)	-0.023 (0.004)	-0.023 (0.004)
$\hat{\mu}_4$ (curvature)	-33.653 (13.519)	-34.304 (13.419)	-34.068 (13.403)	-34.090 (13.488)	-34.139 (13.397)
$\hat{\mu}_5$ (Gender)	-	-0.097 (0.042)	-0.080 (0.043)	-	-
$\hat{\mu}_6$ (Angry&Hostile)	-	-	-0.021 (0.016)	-0.029 (0.015)	-
$\hat{\mu}_7$ (F2234)	-	-	-	-	0.116 (0.044)
$\hat{\sigma}$	0.3639 (0.0145)	0.3616 (0.0143)	0.3607 (0.0142)	0.362 (0.014)	0.361 (0.014)
$\hat{\xi}$	-0.2196 (0.042)	-0.2176 (0.0413)	-0.216 (0.041)	-0.216 (0.041)	-0.217 (0.041)
Neg.LL	208.6541	206.0598	205.2183	206.8908	205.2379

18

1 Analyzing the results presented in Table 1, it is concluded that the inclusion of *Gender* (model #1) improves the  
 2 accuracy of the model when compared to the non-stationary model (#0). The significance of this variable is given  
 3 by the p-value of the likelihood ratio test, which is equal to 0.023 as presented in Table 2, with 95% confidence  
 4 level.

5 **Table 2 Likelihood Ratio Test (and p-value) for the non-stationary BM models for head-on collisions**

Model	#0	#1	#2	#3	#4
#0	-				
#1	5.189 (0.023)	-			
#2	6.872 (0.032)	1.683 (0.194)	-		
#3	3.527 (0.060)	-1.662 (1.000)	3.345 (0.067)	-	
#4	6.832 (0.008)	1.644 (2.2E-16)	0.039 (0.843)	3.306 (2.2E-16)	-

6  
 7 The contribution of the variables representing driving styles (*Angry&Hostile*, *Anxious*, *Reckless&Careless* and  
 8 *Patient&Careful*) was tested considering all the possible combinations of these variables besides the ones included  
 9 in model #1. Comparisons between the different models were based on the likelihood ratio test. This procedure  
 10 resulted in the inclusion of one driving style, *Angry&Hostile*, as presented in model #2. Analyzing the correlation  
 11 between the different driving styles and the sociodemographic variables, a small but significant sample correlation  
 12 of 0.29 was found between *Angry&Hostile* and *Gender*. For modelling purposes, and in order to test which variable  
 13 among the two has a larger influence, the variable *Gender* was excluded from model #2, creating model #3.  
 14 Comparing the results of models #1 to #3, it is concluded that the model that only includes *Gender* (model #1) has  
 15 a better fit based on the p-value of the likelihood ratio test. Although *Angry&Hostile* could have higher explanatory  
 16 power in other samples, a reason to prefer this model is the simplicity of collecting data on driver gender compared  
 17 to drivers' driving styles, which requires the completion of the MDSI survey.

18 Aligned with the conclusions achieved by Farah (2011) and Llorca et al. (2013) regarding the impact of age, this  
 19 variable (*age*) was found to improve the accuracy of the model when compared to the stationary model but turned  
 20 out to have a non-significant contribution if gender is also included. After several attempts, we included the  
 21 interaction variable between gender (female drivers, *Gender*) with age (range 22-34), *F2234*, and the final model  
 22 (model #4) is shown in Table 1. This model considers a new variable that takes 1 if the driver is a female with age  
 23 range between 22 and 34, and zero otherwise.

24 To estimate the probability of a head-on collision along with the conclusion about which model is the one with the  
 25 better fit (models #1 and #4), two different approaches were considered. The first approach considers that the  
 26 location parameter value is calculated using the covariates from the data, achieving the estimated probabilities of

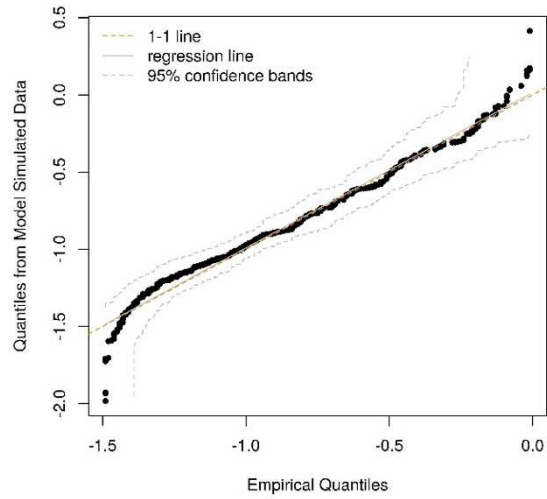
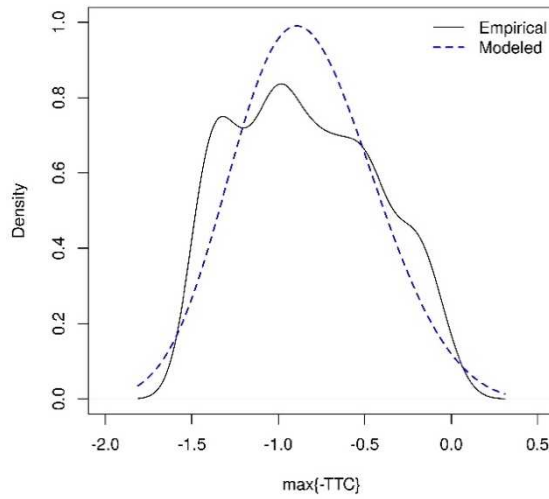
1 0.0195 and 0.0198 for models 1 and 4, respectively, with 95% confidence level (0.0192; 0.0198) and (0.0195;  
2 0.0201), respectively. These confidence intervals of estimation were computed assuming a normal distribution  
3 under regular parameters' conditions, a simulation experiment size of  $1 \times 10^6$  and its simulated distribution  
4 quantiles. The second approach considers the estimation of the location parameters based on the estimation dataset,  
5 where normal distributions with means (standard deviations) of -0.989 (0.123) and -0.988 (0.125), for models #1  
6 and #4, respectively were considered. The Kolmogorov-Smirnov test statistic of 0.0444 and 0.0479, respectively  
7 was achieved. This procedure simulates the values 0.0197 and 0.0202 for the probabilities of head-on collisions of  
8 models 1 and 4, respectively, with 95% confidence interval of (0.01939, 0.0199) and (0.0199, 0.0205). Comparing  
9 the probabilities of these two methods with the probability for a head-on collision assuming a near head-on  
10 collision in a passing maneuver of 0.0191, results in model #1 give a slightly better estimation compared to model  
11 #4 and the estimation performance is not significantly deteriorated.

12 According to the results of model #1 presented in Table 1, if the speed of the front vehicle (*speedfront*) increases,  
13 or if drivers start their passing maneuver from a larger gap from the front vehicle (*tailgatetp*), the negated TTC  
14 increases (corresponding to a decrease in the TTC). These are logical results since it is more difficult to end the  
15 passing maneuver if the front vehicle has a higher driving speed. Similarly, starting the passing maneuver from a  
16 larger gap from the front vehicle results in a longer time to finish the maneuver and consequently smaller TTC. If  
17 the passing gap (*passinggap*) that is accepted is larger, or the curvature of the road (*curvature*) is larger, the negated  
18 TTC is lower and the TTC is higher. This shows that drivers adapt their behavior in a passing maneuver if the road  
19 is too complex (i.e. sharp curves). Finally, male drivers have smaller TTC. This result is supported by previous  
20 studies (Farah et al., 2007; Vlahogianni & Golias, 2012), where it was found that male drivers usually drive faster,  
21 have shorter passing gaps, and conduct a higher number of passing maneuvers when compared to females.

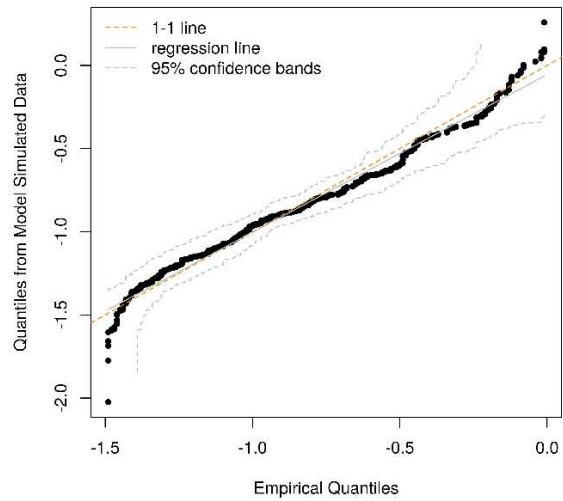
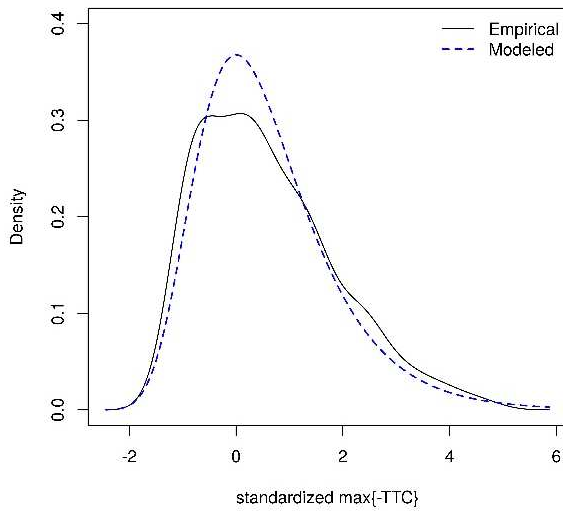
22 The probability density function of the empirical and modeled standardized<sup>2</sup> maximum negated TTC and the  
23 simulated QQ-plot for the best non-stationary BM model (model #1) are shown in Figure 2. From these figures it  
24 can be concluded that the modeled GEV distribution has satisfactory fitting results to the empirical data.

---

<sup>2</sup> For non-stationary models, it is common practice to transform the data to a density function that does not depend on the covariates, using the following function  $Z_i = -\log\left(1 + \frac{\xi}{\sigma} \times (X_i - \mu_i)\right)^{-\frac{1}{\xi}}$ , Gilleland and Katz (2011).



1



2

3 **Figure 2 Probability Density plots (left) and simulated QQ-plots (right) for the stationary BM model (top)**  
 4 **and the best non-stationary BM model (model #1, bottom) for head-on collisions.**

5

#### 6 4.1.2 Rear-end collisions

7 In order to estimate the probability of rear-end collisions, the headway between the passed vehicle and the passing  
 8 vehicle at the end of the passing maneuver (THW) is used as accident surrogate. Similarly to the probability  
 9 estimation process for head-on collisions, the minimum THW should be smaller than a limit to be useful as an  
 10 accident surrogate. Based on the literature, this value varies between  $<0.6s$  (Vogel, 2003) and  $<2.0s$  (Evans &  
 11 Wasielewski, 1982; Vogel, 2003). Considering these thresholds, several BM stationary models were developed  
 12 and evaluated (see Appendix 2) and the value of  $2.0s$  was ultimately adopted.

1 With a total of 492 observations with a THW smaller than 2.0s and knowing that 2 rear-end collisions occurred,  
2 the theoretical probability of a rear-end collision was calculated as  $2/(492+2)= 0.00405$ , with a 95% binomial  
3 confidence interval  $(-0.00155, 0.00964)$ .

4 The estimation of the stationary BM for the model of the negated values of the THW as carried out using the  
5 Gumbel distribution as the stable region for the shape parameter around the 2.0s THW filter resulted in  $\hat{\xi} \approx 0$ .  
6 Further, as explored in Appendix 2, we use the normalized dataset  $\tilde{X}_i = -X_i - \max_{j=1}^n (-\{X_j\})$ ,  $X_i$  being the  
7 THW for observation  $i$ , that was proven to provide a better prediction performance. Thus, we obtained the  
8 parameters  $\hat{\mu} = -1.456$  (0.0121),  $\hat{\sigma} = 0.256$  (0.0093) and  $\hat{\xi} = 0$ . The density function of the empirical and  
9 modeled negated THW and the simulated QQ plot are shown in Figure 3. Due to the small sample and high  
10 variance of the surrogate measure at stake (low THW) the non-normalized BM estimation resulted in positive  
11 shape parameter for low filtering conditions.

12 Using the fitted Gumbel distribution to the normalized data, the estimated probability of this stationary model is  
13 0.00334 with 95% confidence interval (0.00317, 0.00340). This interval was computed assuming a normal  
14 distribution under regularity conditions of the parameters, simulating an experiment with a size of  $1 \times 10^6$  and its  
15 simulated distribution quantiles. This estimated probability is relatively close to the empirical probability of  
16 0.00405. Notwithstanding, the passing maneuver may be affected by specific passing conditions, such as speeds  
17 of the vehicles surrounding the subject vehicle. Therefore, several linear combinations of covariates were tested  
18 according to a non-stationary BM model approach. This process was conducted in a similar way to the model  
19 developed to estimate the probability of a head-on-collision.

20 Taking this into account, we start with the non-stationary BM model #0, which includes the covariates related with  
21 the maneuver and the environment that were found to be significant during the estimation: passing vehicle speed  
22 (*speedpv*) and the passing gap time (*passinggap*). Testing this non-stationary model against the stationary one  
23 through the likelihood ratio test, a p-value of 0.0002 is achieved with a direct value of 17.508 (note, 2 degrees of  
24 freedom). We then estimate the probability of a rear-end collision for a single passing maneuver (see Appendix  
25 2). This distribution with a mean of -1.454, a standard deviation of 0.0232 and a Kolmogorov-Smirnov test  
26 statistic of 0.025, lead to a simulated rear-end collision probability of 0.00339 with 95% confidence interval  
27 (0.00328, 0.00351), resulting in a slightly better estimation than the stationary model. The probability density plot  
28 as well as the QQ-plot for model #0 are shown in Figure 3.



**Table 3 Estimation results of the non-stationary BM approach for rear-end collisions**

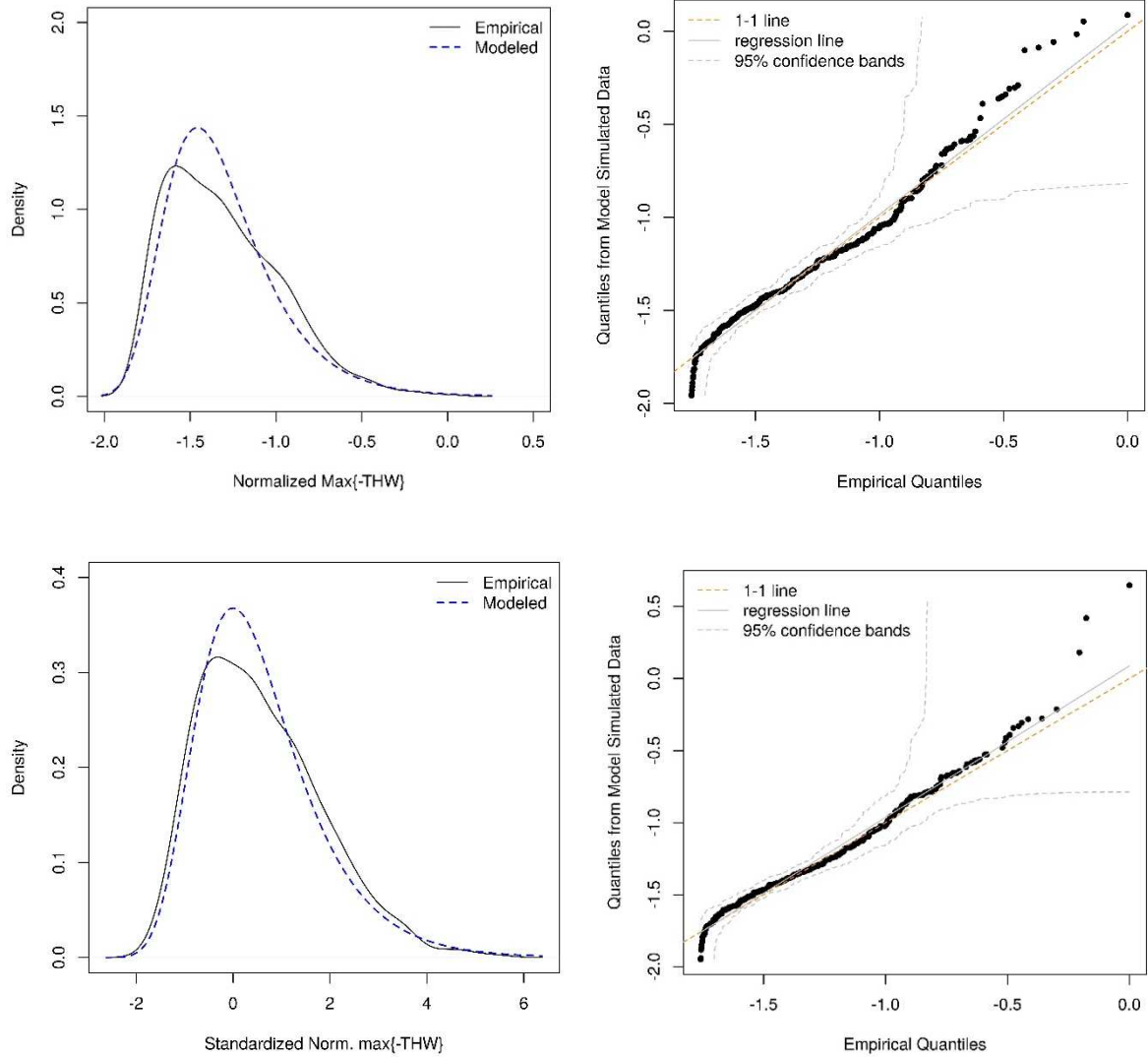
Non-stationary model	#0	#1	#2
	Est. (Std. Error)	Est. (Std. Error)	Est. (Std. Error)
$\hat{\mu}_0$	-1.42 (0.0626)	-1.37 (0.0653)	-1.42 (0.0694)
$\hat{\mu}_1$ (speedpv)	0.00587 (0.00193)	0.00686 (0.00198)	0.00673 (0.00197)
$\hat{\mu}_3$ (passinggap)	-0.00916 (0.00263)	-0.0101 (0.00267)	-0.0107 (0.00271)
$\hat{\mu}_5$ (Gender)	-	-0.0590 (0.0282)	-0.0753 (0.0296)
$\hat{\mu}_6$ (Angry&Hostile)	-	-	0.0185 (0.00992)
$\hat{\sigma}$	0.254 (0.00914)	0.253 (0.00910)	0.252 (0.00906)
$\hat{\xi}$	0	0	0
Neg.LL	104.09	101.98	100.26

**Table 4 Likelihood Ratio Test (and p-value) for the non-stationary BM models for rear-end collisions**

Model	#0	#1	#2
#0	-		
#1	4.23 (0.0398)	-	
#2	7.657 (0.0218)	3.43 (0.0640)	-

From all models including driver's characteristics, Table 3 presents the two best models for rear-end collisions, which actually relied in the same key co-variates as the head-on collision estimation results. While age related co-variates didn't bring any improvement in the estimation results, *Gender* and *Angry&Hostile* co-variates managed to improve it. Again, the significance of these variable is given by the p-value of the likelihood ratio tests presented in Table 4. We note again the correlation found between these two variables and as previously discussed, followed with model #1 in the rest of this paper.

Similarly to the head-on estimates, two different approaches were considered for probability estimation. The first approach considers that the location parameter value is calculated using the covariates from the data. The second approach considers the estimation of the location parameter distribution based on the estimation dataset. The estimated probabilities of 0.00333 and 0.00337, respectively, with 95% confidence level (0.00322; 0.00345) and (0.00326; 0.00349) were obtained. All confidence intervals of estimation were computed assuming a normal distribution under regular parameters' conditions, a simulation experiment size of  $1 \times 10^6$  and its simulated distribution quantiles.



1

2

3 **Figure 3 Probability Density plots (left) and simulated QQ-plots (right) for the stationary BM model (top)**  
 4 **and the non-stationary BM model (model #1, bottom) for rear-end collisions.**

5 In summary, the univariate fitting resulted in a non-stationary GEV with *speedFront*, *tailgatetp*, *passinggap*,  
 6 *curvature* and *Gender* as scale-specific covariates for head-on collisions and a non-stationary Gumbel with  
 7 *speedpv*, *passinggap* and *Gender* as scale-specific covariates for rear-end collisions as the best models. One can  
 8 interpret that the scale is larger in TTC and the tails (shape) are much lighter (close to 0) for THW which shows a  
 9 significant different behavior between the two. Interestingly, Zheng and Sayed (2019b) also reported similar  
 10 findings for the univariate GEV of similar surrogate safety measures but in a very different context (crossing  
 11 maneuvers). Ultimately and as shown in Annex 2, understanding the behavior of the fitted distributions and its  
 12 theoretical suitability for each application at stake needs to be carefully handled both at the level of improving  
 13 estimation or/and at the level of defining the safety index, as very little applications to road safety are yet available.

## 1    **4.2    Bivariate Model**

2    It is aimed to estimate a measure of risk that not only takes into account the possibility to collide with the opposite  
3    vehicle but also with the passed vehicle. Performing a passing maneuver requires a split of attention by the driver  
4    regarding its location relative to the surrounding vehicles, and in this case mainly the opposite and lead vehicle.  
5    As drivers attempt to keep larger gap from the passed vehicle, this directly means that the gap from the opposite  
6    vehicle will be smaller, assuming constant speeds of the opposite and passed vehicles. In other words, there might  
7    be a correlation between these two surrogate safety measures. In this paper, it is assumed that the dependence  
8    between the TTC and the THW is unknown. Furthermore, an integrated analysis is possible to be developed if,  
9    and only if, a relationship of dependence can be found between TTC and THW. When examining the correlation  
10    between these two variables with using the whole dataset, a Pearson-correlation value of 0.186 was found. This  
11    value shows the lack of linear correlation between the TTC and THW. However, this does not mean that TTC and  
12    THW are independent (Embrechts, McNeil, & Straumann, 2002). To further examine potential correlation, the  
13    Kendall's rank correlation  $\tau$  was computed and found to be significantly greater than zero, indicating the existence  
14    of dependence between TTC and THW ( $\tau=0.192$ ,  $p\text{-value}<2.2\times 10^{-16}$ ). This statement is corroborated by the  
15    independence test Global Cramer-von Mises, where a significant p-value close to zero ( $p\text{-value}=0.000499$ ) gives  
16    evidence against the null hypothesis of independence.

### 17    **4.2.1    Stationary Marginals**

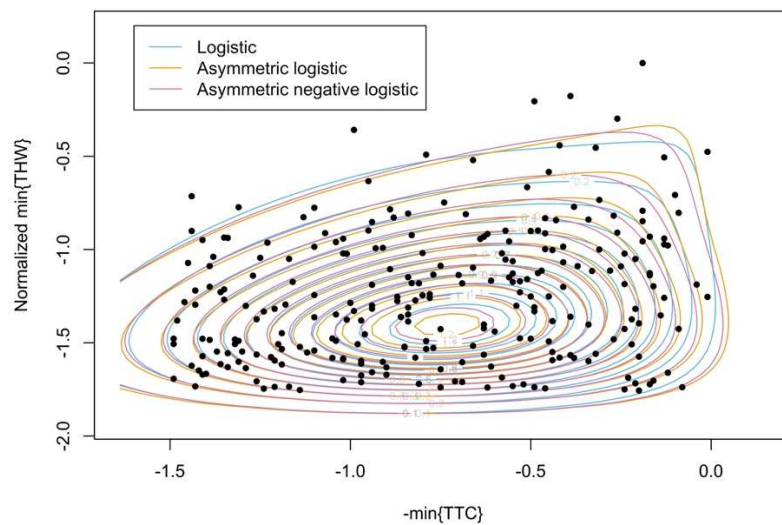
18    Due to Sklar's Theorem (Sklar, 1959) any multivariate distribution can be expressed in terms of its marginals and  
19    the copula (see Section 3.3). Hence, in a first stage we estimated the marginals separately, considering the  
20    stationary univariate BM distributions for each variable. By the probability integral transform the marginals turn  
21    to approximately uniform variables, used next to copula estimation that contains all the dependence information.  
22    Depending on the selected copula-parametric model, its dependence parameters are consequently estimated. This  
23    integration estimates the probability of an accident conditioned on TTC and THW being smaller than their filters  
24    (1.5s and 2.0s, respectively). Recall that these filters are the established limits for the variables to be useful as an  
25    accident surrogate. Since a marginal fitting is necessary prior to the dependence fitting, we think it is more coherent  
26    to use only the specific sample information related to accident surrogate. Thus, to perform the estimation for the  
27    remaining TTC and THW sample, other distributions for the margins should be tested (e.g., gamma distributions).  
28    This is mainly due to the reported non-extreme value distribution of safety measures beyond surrogate safety  
29    analysis conditions.

1 Using the R package `evd` (Stephenson, 2002), we explored different bivariate functions: logistic, asymmetric  
2 logistic, Husler–Reiss, negative logistic, asymmetric negative logistic and bilogistic. For further details on its  
3 formulation and implementation in R the reader is referred to the `evd` package documentation (Stephenson, 2002).  
4 Here we present the results for the distributions with the highest AIC and predictive power: logistic; asymmetry  
5 logistic and asymmetric negative logistic distributions. The bivariate logistic distribution function has underlying  
6 dependence parameter  $r$  (within the dependence function  $A$  in Eq. 6 above) where complete dependence is  
7 obtained in the limit as  $r$  approaches zero (and independence is obtained when  $r = 1$ ). It is a special case of the  
8 asymmetric logistic model where two additional asymmetry parameters are considered within  $A$ . Here,  
9 independence is obtained when  $r = 1$  or when the asymmetry parameters equal 0. Complete dependence is  
10 obtained in the limit when the asymmetry parameters are equal to 1 and  $r$  approaches zero. The asymmetric  
11 negative logistic distribution is equivalent to the negative logistic model. Independence is obtained in the limit as  
12 either  $r$  or the asymmetry parameters approaches zero. Complete dependence is obtained in the limit when the  
13 asymmetry parameters are equal to 1 and  $r$  tends to infinity (Capéraà & Fougères, 2000; De Haan & Ferreira  
14 2006). The results are presented in Table 5. The estimated probability was obtained from the estimated joint  
15 cumulative distribution function and considering either and both of the surrogate measures equal or less than zero  
16 (see Appendix 1).

17 **Table 5 Estimation results for the stationary parametric bivariate BM model for the Logistic, Asymmetric**  
18 **Logistic and Asymmetric Negative Logistic and the best Copula based model (Joe-Frank)**

	Parameter	Logistic	Asym. Log.	Asym. Neg. Log.	Joe-Frank Copula
Marginals	$\hat{\mu}_{TTC}$	-0.886 (0.031)	-0.877 (0.031)	-0.883 (0.031)	-0.886 (0.031)
	$\hat{\sigma}_{TTC}$	0.431 (0.024)	0.445 (0.026)	0.431 (0.024)	0.432 (0.025)
	$\hat{\xi}_{TTC}$	-0.417 (0.060)	-0.424 (0.069)	-0.415 (0.062)	-0.432 (0.059)
	$\hat{\mu}_{THW}$	-1.417 (0.021)	-1.422 (0.021)	-1.421 (0.021)	-1.417 (0.019)
	$\hat{\sigma}_{THW}$	0.280 (0.016)	0.283 (0.016)	0.280 (0.016)	0.280 (0.014)
	$\hat{\xi}_{THW}$	-0.0008 (0.060)	-0.0059 (0.061)	-0.0017 (0.058)	-
Dependence	$r$	0.865 (0.039)	0.774 (0.100)	0.580 (0.154)	-
	$Asym_1$	-	0.497 (0.328)	0.379 (0.199)	-
	$Asym_2$	-	0.999 ( $2 \times 10^{-6}$ )	0.999 ( $2 \times 10^{-6}$ )	-
	$\theta$	-	-	-	1.815 (1.101)
	$\delta$	-	-	-	0.729 (0.384)
	AIC	419.197	422.948	421.043	418.4
	Estimated Probability	0.0141	0.0190	0.0149	0.0209

1 The empirical probability for comparison was calculated by knowing that a maximum of 5 (4 head-on and 1 rear-  
 2 end collisions) out of the total 11 collisions had the other surrogate safety measure value below its filter (i.e., if  
 3 head-on collision, then THW was below 2.0 s, and if rear-end collision, then the TTC was below 1.5 s), and that  
 4 the sample of size is given by the number of collisions plus the 256 observations where both TTC and THW were  
 5 below 1.5 and 2.0, respectively. Therefore, the empirical collision probability is 0.0191 (0.0025, 0.0358). Despite  
 6 slightly higher AIC, the asymmetric negative logistic distribution was able to provide better probability estimates.  
 7 Note again the obtained shape parameter for the THW marginal close to zero.

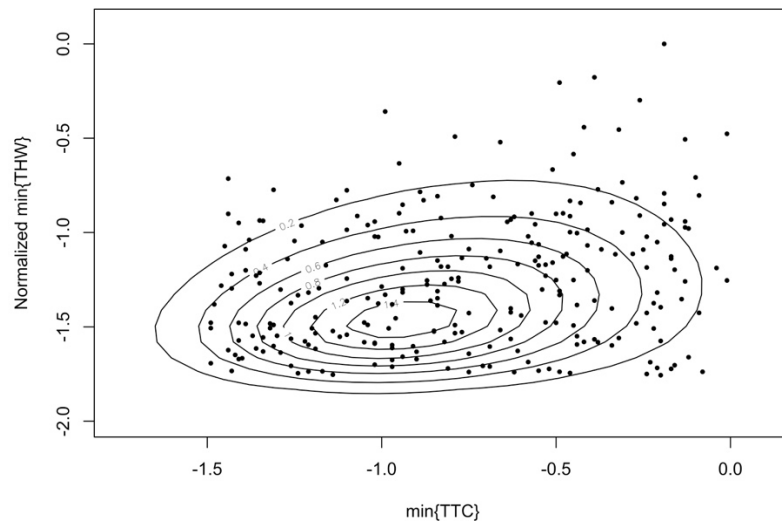


8  
 9 **Figure 4 Probability density contours for stationary bivariate EV distributions and the observed data.**

10 Further explore non-EV copula families to model the dependence between the negated values of TTC and of  
 11 (normalized) THW using the range of families available in the R packages `vineCopula` and `copula` (namely,  
 12 Gaussian, Student t, Clayton, Gumbel, Frank, Joe, Joe-Gumbel, Joe-Clayton, Joe-Frank and their rotations). To  
 13 explore these families the marginals are estimated first (as per the previous section 4.1 of this paper), and the  
 14 copula is here estimated subsequently. We first concluded that the copula with the best AIC is the Joe-Frank  
 15 (Brechmann & Schepsmeier, 2013), with parameters 1.95 and 0.71. This result was also confirmed by performing  
 16 the goodness-of-fit test based on Kendall's process (0.67 for both p-values of Cramer-von Mises statistic and  
 17 Kolmogorov-Smirnov statistics). Simulating elements for the copula distribution analyzed in this exploratory  
 18 approach, with a Joe-Frank copula and GEV (TTC) and Gumbel (THW) distributions for the margins, a maximum  
 19 log likelihood of -202.2. Using this fitted distribution (see Table 5), the estimated probability of having an accident,  
 20 conditioned that both surrogate measures are below their filter, was slightly overestimated at 0.0209 (0.0206,

1 0.0212). For head-on collisions the obtained probability is 0.0178 (0.0175, 0.0181) and for rear-end collisions  
2 0.0033 (0.0032, 0.0034).

3 The probability density function of this bivariate model is displayed in Figure 5. The dependencies obtained for  
4 both the full maximum likelihood estimation under the bivariate EV distribution functions or the non-EV Copula-  
5 based estimation for the Joe-Frank copula revealed the suitability of our approach to estimate the joint probability  
6 of an accident based on the two surrogate measures (TTC and THW). Yet, as previously mentioned, further  
7 analysis should be performed with approaches such as other EV and non-EV copulas together with the inclusion  
8 of other distributions for the margins should be explored (Capéraà, Fougères, & Genest, 1997).



9

10 **Figure 5 Probability density contour for the stationary Joe-Frank copula and the observed values.**

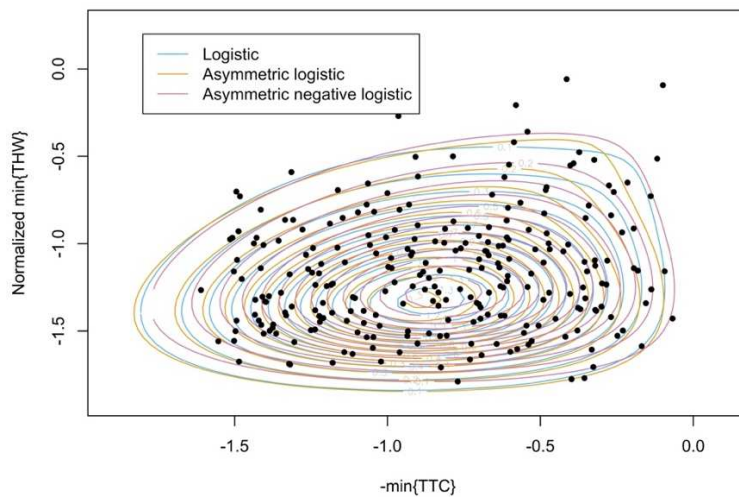
#### 11 4.2.2 Non-stationary Marginals

12 As in the univariate case, we now aim at studying the importance of driver characteristics in the estimation of  
13 collision probability under the bivariate approach. Such analysis allows us to shed light on these variables in the  
14 interactions between the driver, the opposing and the passed vehicle. We consider again the covariates selected in  
15 the best univariate BM models and we estimate the three bivariate EV distributions from section 4.2. A bivariate  
16 BM model was fitted to the joint distribution of  $\max\{-TTC\}$  and (normalized as detailed in as in Appendix 2)  
17  $\max\{-THW\}$ , achieving the parameters shown in Table 6 and the contours shown in Figure 6. Both the dependence  
18 and the predictive power improve significantly, while keeping the signs and magnitude of the covariates consistent  
19 with the phenomenon at stake and the previous estimations. All confidence intervals for the estimated probabilities  
20 were again computed assuming a normal distribution under regular parameters' conditions and a simulation  
21 experiment size of  $1 \times 10^6$ .

1  
2

**Table 6 Estimation results for the non-stationary bivariate BM model for the Logistic, Asymmetric Logistic and Asymmetric Negative Logistic**

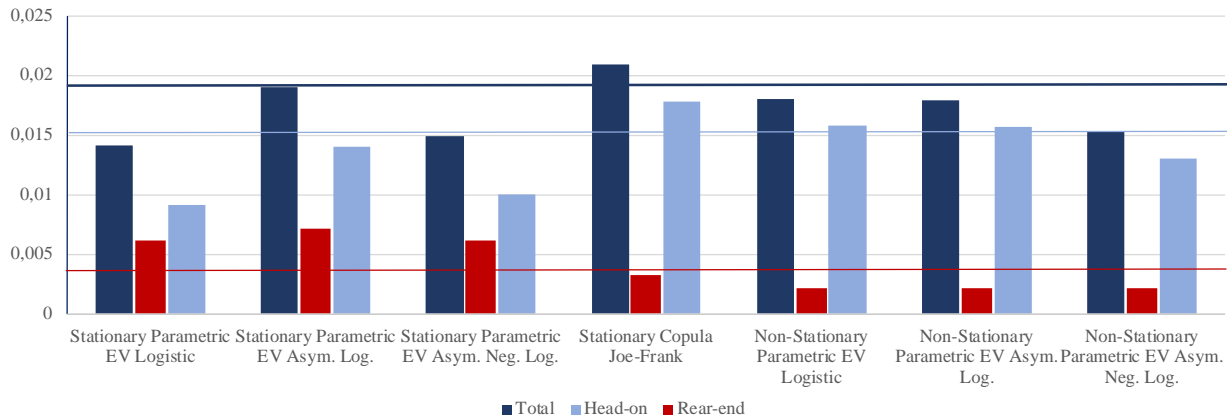
Parameter	Logistic	Asym. Log.	Asym. Neg. Log.
$\hat{\mu}_0^{TTC}$	-1.004 (0.177)	-1.018 (0.177)	-0.958 (0.170)
$\hat{\mu}_{speedFront}^{TTC}$	0.028 (0.009)	0.028 (0.009)	0.025 (0.009)
$\hat{\mu}_{tailgatetp}^{TTC}$	0.004 (0.002)	0.0033 (0.002)	0.033 (0.002)
$\hat{\mu}_{passinggap}^{TTC}$	-0.022 (0.006)	-0.021 (0.005)	-0.021 (0.006)
$\hat{\mu}_{curvature}^{TTC}$	-31.193 (19.231)	-34.777 (19.44)	-34.790 (18.505)
$\hat{\mu}_{Gender}^{TTC}$	-0.076 (0.060)	-0.061 (0.061)	-0.063 (0.061)
$\hat{\sigma}^{TTC}$	0.400 (0.023)	0.398 (0.023)	0.397 (0.023)
$\hat{\xi}^{TTC}$	-0.366 (0.068)	-0.371 (0.071)	-0.381 (0.068)
$\hat{\mu}_0^{THW}$	-1.353 (0.115)	-1.358 (0.116)	-1.312 (0.114)
$\hat{\mu}_{speedPV}^{THW}$	0.014 (0.004)	0.014 (0.004)	0.013 (0.004)
$\hat{\mu}_{passinggap}^{THW}$	-0.016 (0.005)	-0.016 (0.005)	-0.017 (0.005)
$\hat{\mu}_{Gender}^{THW}$	-0.103 (0.045)	-0.104 (0.046)	-0.110 (0.045)
$\hat{\sigma}^{THW}$	0.281 (0.015)	0.283 (0.015)	0.277 (0.014)
$\hat{\xi}^{THW}$	-0.008 (0.049)	-0.083 (0.050)	-0.073 (0.049)
$r$	0.907 (0.037)	0.813 (0.099)	0.456 (0.195)
$Asym_1$	-	0.277 (0.202)	0.350 (0.336)
$Asym_2$	-	0.999 ( $2 \times 10^{-6}$ )	0.999 ( $2 \times 10^{-6}$ )
AIC	395.396	397.553	397.85
Estimated Probability	0.0180 (0.0178,0.0183)	0.0179 (0.0176,0.0181)	0.0153 (0.0149,0.0154)



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**Figure 6 Probability density contour plot for the best non-stationary bivariate distributions and the observed data.**

1 In Figure 7 we present the summary of the estimated probabilities for all best models presented above, and its  
 2 empirical values.



3  
 4 **Figure 7 Probability estimates for all best bivariate models (empirical values as horizontal lines).**

5  
 6 As a final comparison, and as in the previous sections, we look at the obtained AIC, the amplitude of the estimates'  
 7 confidence interval reflecting higher precision, and the prediction power (estimated probabilities) of each model.  
 8 The non-stationary parametric asymmetric logistic bivariate EV seems to perform better overall. More  
 9 interestingly, and having in mind the considered surrogate safety measures, the models that perform best in terms  
 10 of these three criteria are not the ones with the strongest dependence, especially noticing that the same model with  
 11 covariates increases the degree of independence. Thus, we are consistently observing weak dependence between  
 12 the two indicators. Also, adding the covariates allowed once again to improve the overall performance of all  
 13 models.

## 14 5 Conclusions

15 This paper analyzed the individual and joint probabilities of head-on collisions and rear-end collisions through the  
 16 Block Maxima approach using the Univariate and Bivariate distributions to model dependence between the two  
 17 surrogate measures that capture those types of collisions during passing maneuvers.

18 We investigated the fitting of EV models allowing for any real extreme value index, to understand how informative  
 19 these models may be in respect to the extreme value indices pertaining to surrogate measures of safety.

20 The univariate non-stationary estimation allowed to conclude that aspects linked to drivers' characteristics, namely  
 21 the driving style/gender, have a significant impact on the prediction of collisions. Furthermore, we show how  
 22 different measures may have different behaviors that need for careful EV theoretical and application-specific  
 23 attention. In future application, understanding such behavior of the fitted distributions and its theoretical suitability



1 for each application at stake needs to be handled both at the level of improving estimation or/and at the level of  
2 defining the safety index, as very little applications to road safety are yet available. Furthermore, with the increased  
3 availability of comprehensive naturalistic datasets, we hope that EV approaches will be able to provide a robust  
4 quantified link between driver's characteristics, detailed surrogate safety measures and the instant probability of  
5 different types of accidents.

6 The bivariate model approach integrated the two different surrogate measures, TTC and THW, in order to estimate  
7 the risk of colliding with the opposite or with the passed vehicle in a single passing maneuver. Although the linear  
8 correlation between the two surrogate measures has proved to be weak, the bivariate distribution estimation shown  
9 the existence of dependency between these two surrogate measures, relative improved the predictive power of the  
10 EV model and set the ground for further the exploration of multi-variate and copula EV approaches in complex  
11 road safety phenomena. However, the models that perform best in terms of fit and prediction power are not the  
12 ones with the strongest dependence, especially noticing that the same model with covariates increases the degree  
13 of independence. Also, adding the covariates allowed to improve the overall performance of all models.

14 In terms of future work, and regarding the rear-end collisions model estimation, we suggest that the fitting must  
15 concentrate on the more theoretically consistent Gumbel or Weibull distributions under the BM approach and GP  
16 distributions restricted to non-positive extreme value index under POT approach to improve precision on accident  
17 probability estimation especially under small samples. Further exploration of the wide range of Copula family  
18 models should also be explored in the field of road crash probability estimation based on surrogate safety measures.

19 To sustain the preliminary conclusions that both TTC and THW are good surrogate safety measures for near-  
20 accidents, head-on collisions and/or rear-end collisions, further analysis should be developed in order to validate  
21 through simulated data and/or data from other experimental scenarios the conclusions drawn by these models.

22 Finally, following the very recent univariate applications (Wang, Xu, Xia, Qian & Lu, 2019), the proposed  
23 multivariate probabilistic surrogate safety models should be integrated in traffic microscopic simulation  
24 frameworks and advanced vehicle control and driving assistance systems for promising safety assessment, where  
25 the estimation of safety for individual maneuvers would not need to rely on accident records nor on the limitations  
26 of simulation's and algorithm's premise of accident-free models.

27

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- 43

## 1    **6    Appendix 1: Probability of Collision**

2    The maximum domain of attraction condition holds if, for  $\{-X_1, \dots, -X_n\}$  an i.i.d. sample of the surrogate measure  
 3    of safety  $x$ ,

$$4 \quad \exists a_n > 0, b_n \in \mathbb{R}: \lim_{n \rightarrow \infty} P\left(\frac{\max_{i \leq n} -X_i - b_n}{a_n} \leq y\right) = e^{-\left(1 + \frac{\xi(y-u)}{\sigma}\right)_+^{\frac{1}{\xi}}}, \xi \in \mathbb{R} \quad (\text{Eq. 8})$$

5    with  $1 + \xi \frac{(y-u)}{\sigma}$  always positive. This formulation simplifies to a standard EV in the limit if  $a_n$  and  $b_n$  are chosen  
 6    appropriately. Hence under the BM approach we define:

$$7 \quad P_{BM}(\text{collision}) = \lim_{n \rightarrow \infty} P\left(\frac{\max_{i \leq n} X_i - b_n}{a_n} \geq 0\right) = \lim_{n \rightarrow \infty} P\left(\max_{i \leq n} X_i \geq b_n\right) \quad (\text{Eq. 9})$$

8    and estimate it by,

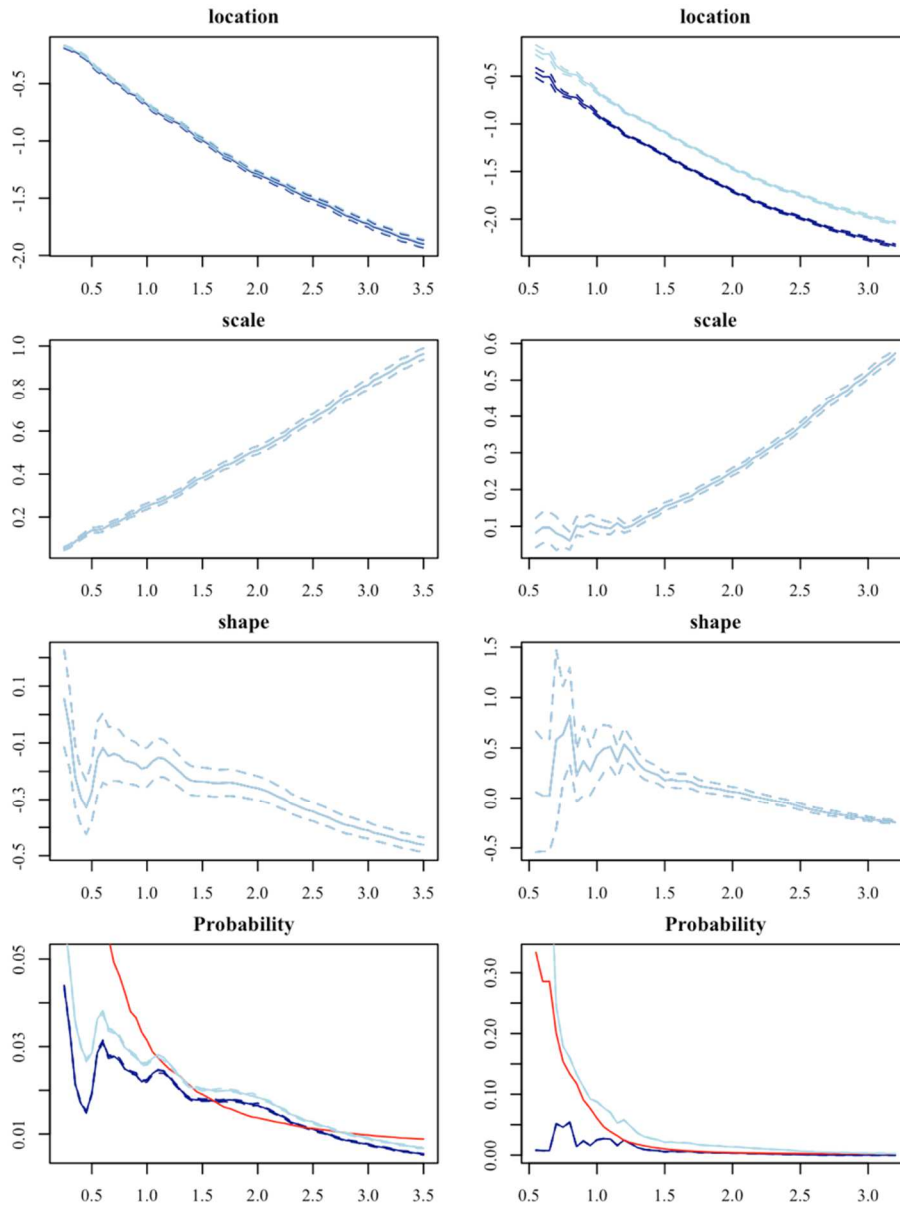
$$9 \quad \hat{P}_{BM}(\text{collision}) = 1 - e^{-\left(1 - \frac{\xi \hat{u}}{\sigma}\right)_+^{-1/\xi}} \quad (\text{Eq. 10})$$

10    The above equation can also be interpreted as estimating the probability until achieving that “least real value” of  
 11    the surrogate safety measure before collision, or approximately the probability of this measure being as close to  
 12    zero up to the actual observed sample maximum.

## 13    **7    Appendix 2: Summary of the Stationary Model Estimation and Filter Sensitivity Analysis**

14    To validate the TTC and THW filter used in Section 4, a sensitivity analysis was performed. This analysis allows  
 15    not only to analyze the stability of the estimation in the selection of the filter, but also to explore the range of shape  
 16    parameter values to be expected in non-stationary estimation. It also allows to evaluate the prediction performance  
 17    of a simplified stationary approach. We also computed the estimates for the normalized model with  $\{a_n, b_n\} =$   
 18     $\{1, -\min(X_i)\}$  with  $i \in 1, \dots, n$  for the BM and study it’s performance compared to the non-normalized model.  
 19    Such normalization can be of particular relevance under small samples and increased variability of the observed  
 20    variables.

21    In Figure 8 we present the results for BM approach. The red curve in the bottom plot represents the empirical  
 22    conditional collision probability from the used data. We first highlight the stable region for the estimate of the  
 23    shape parameter for TTCs between 0.6 and 1.5s (head-on collision). The normalized model does not provide  
 24    significant prediction improvement nor different estimates (as the dark blue and light blue curves for parameter  
 25    estimates are overlapping), likely due to a large number of surrogate observations. From the analysis values  
 26    between 1.2 and 1.5 s are likely to provide both good statistical properties and prediction performances. The value  
 27    of 1.5s was thus selected for further analysis due to its smaller variance.



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**Figure 8 ML estimates of the univariate stationary BM location, scale and shape parameters and the resulting probability of collision for the TTC (left) and the THW (right) for the original (dark blue) and normalized (light blue) model for different filtering criteria. In red is the empirical conditional collision probability.**

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A first stable region for the estimate of the shape parameter for THWs happens between 1.0 and 1.3s (rear-end collision). However, within this region the shape parameter has positive values (between 0.35 and 0.55) therefore conflicting with the theory, since a positive shape parameter implies an infinite right-endpoint for the underlying distribution of THW (as explained in Section 3.2). These results are mainly due to the small sample (<100 observations) and the high variability of THW within this region. Thus, we further explore the stable region between 2.0 and 2.4s where the shape parameter has values close to zero (between 0.06 and -0.05). The Gumbel

1 distribution (GEV with  $\xi = 0$ ) was tested within this region and used for further analysis. Finally, due to  
2 limitations of the THW dataset mentioned above, it is worth noting the increased prediction performance of the  
3 normalized model.