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Analyzing road near departures as failure-caused events

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ABSTRACT

Surrogate measures of safety attract revived interest thanks to the advancements in traffic observations techniques and the growing need for rapid safety evaluation. A new method of safety analysis based on failure-caused traffic conflicts and the Lomax distribution was recently proposed to estimate crash frequency more efficiently than with crash data. This paper has two objectives: (1) demonstrate the method applicability to near-departure data collected in a driving simulator, and (2) provide initial evidence of the method validity.

Traffic failures and road users' delayed responses to these failures is considered as the primary cause of both conflicts and crashes. Unlike early postulated exceedance distributions the proposed Lomax distribution of response delays was derived from the causal mechanism. From this perspective, the proposed method may use the entire range of the underlying distribution as long as the observed conflicts are failure-related.

The fundamentals of the method are briefly explained with the emphasis on certain behavior of crash frequency estimates implied by the proposed theory. Then, an example application of the method to analyze the risk of road departures in a driving simulator is presented. The results are then inspected and the trend in the estimates derived from the theory is confirmed. This finding points to the method validity. Additional applications of the method are expected to further increase the confidence towards the method and to encourage its introduction to the safety engineering practice.

1. Introduction

The new technologies emerging into the road transportation are expected to considerably affect the road safety. The most prominent and potentially consequential technology is connected and automated vehicles. The road safety and its way of managing and improving are likely to be strongly affected. Crashes will become less frequent while the risk perception and public attention to road safety may increase. There is no doubt that the crash-based safety analysis method will require a supplemental method that with time may replace the crash-based approach. Safety-relevant traffic conflicts are regaining their importance in recent years and they are becoming the most promising basis of safety analysis alternative to reported crashes. It is not surprising that US DOT (2017) recommended evaluation and improvement of the emerging vehicles technologies based on analyzing pre-crash scenarios that are the essence of traffic conflicts and other safety-relevant events. The term *pre-crash* prompts a looming crash and a temporarily undesirable situation. This connotation puts a traffic conflict, understood as a result of a failure, to the center of attention. This failure, whether of a human driver today or of a driving machine tomorrow, is the causal analogy between traffic conflicts and crashes because crashes are neither intentional nor allowed by design.

The earliest use of the term *traffic conflict* was found in Klebelsberg (1964) and its first application to identify safety-related problems is attributed to the Detroit General Motors Laboratory (Perkins and Harris, 1968). It seems that over time the definition of traffic conflicts has become more specific and more focused. Perkins and Harris (1968) included traffic violations without imminent danger among traffic conflicts. Red signal violation was considered a traffic conflict even without interaction with vehicles entering an intersection. Hayward (1971) narrowed the meaning of traffic conflicts to dangerous interactions between road users. The first Workshop on Conflict Techniques in Oslo in 1977 introduced a formal definition of traffic conflicts as observable situations "in which two or more road users approach each other in space and time to such an extent *that there is a risk of collision if their movements remain unchanged*." Oslo's definition was further modified in the Dutch method DOCTOR (van der Horst and Kraay, 1986) by adding the condition of an outcome sufficiently severe to be "recordable." Since none of these definitions explicitly mention failure as a necessary condition of claiming a conflict, it is possible today to apply the concept of traffic conflicts to aggressive behaviors where the closeness of road users is intentional and controlled.

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The current editing tool mode is far from perfect. Its weird behavior forced me to use four comments in one sentence of the manuscript to explain the needed corrections. Instead, I should be able to edit the text myself in a fraction of time. The tool sometimes allows it and simetimes does not. I wasted my time trying to figure out what I was doing differently than previously and I couldn't. Someone else will waste an additional time on incorporating my comments. The tool should be improved.

The early studies aimed to connect the frequency of conflicts with the frequency of crashes on various roads and in various conditions with a single crash-conflict ratio. All the early attempts utilized crash data reported in long periods and traffic conflicts observed in representative short periods (Migletz et al., 1985; Hydén, 1987; El-Basyouny and Sayed, 2013). To reach a reasonable confidence of the estimate, multiple sites had to be included and obtaining a reliable estimates of the crash-conflict ratio was found difficult due to: possibly improper aggregation of data from heterogeneous sites, underreporting of crashes, ambiguous definitions of crashes and conflicts, different conditions of crashes and conflicts occurrence in different observation periods, and variability of conflict and crash counts across sites.

In 1980, Glauz and Migletz presented a novel idea of bridging conflicts with crashes (Glauz and Migletz, 1980) by viewing them as safety-relevant events with a common distribution of crash nearness (Fig. 1). The two authors considered their concept as "philosophical considerations in traffic conflict definitions" and not a practical avenue towards estimating the frequency of crashes via observing conflicts. The approach was eventually implemented 16 years later by Campbell et al. (1996) who used the Weibull distribution. Unaware of the Campbell's unpublished research report, Songchitruksa and Tarko proposed 10 years later the extreme value statistics to estimate the probability of a right-angle crash at signalized intersections (Songchitruksa, 2005; Songchitruksa and Tarko, 2006). To increase the estimation efficiency in their consecutive work, Tarko and Songchitruksa used exceedance statistics and the Generalized Pareto distribution (Tarko and Songchitruksa, 2005; Tarko, 2012). Zheng et al. (2014a, 2014b) confirmed that exceedance-based estimation was more efficient than that estimation based on extreme values.

Checking the validity of the method based on the extreme value theory is a challenging task. The distribution postulated by this theory is just an asymptotic approximation of the actual distribution and as such, it does not refer to the crash occurrence process. Thus, the only way to confirm the results validity is comparing the expected number of crashes obtained from the method to the observed crashes. For practical

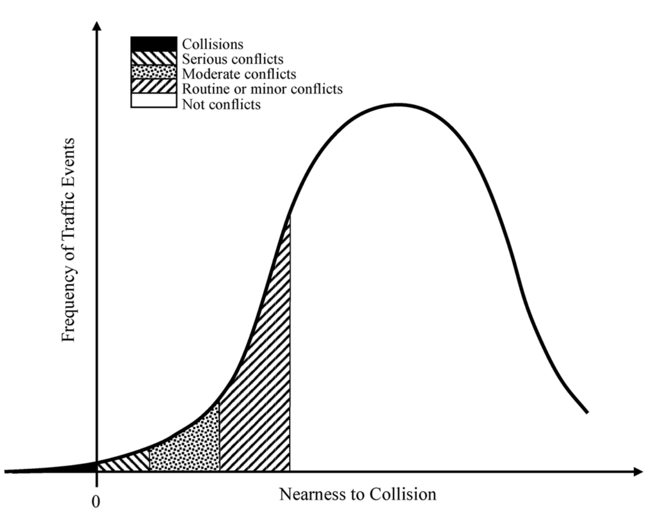

Fig. 1. Concept of the continuous distribution of crash nearness as a bridge between crashes and traffic conflicts and other safety-relevant events (redrawn and modified based on Glauz and Migletz, 1980).

reasons, the period with reported crashes must be much longer than the period of observing conflicts. The results are subject to random fluctuations of the counts and to inconsistency of the conditions in the two periods. Underreporting of crashes is the additional hurdle.

Rather than extrapolating distribution tails into unobserved events without considering the crash-generation mechanism, as it is done in the extreme value method, another approach considers a crash as a counterfactual outcome of an observed traffic conflict. The work by Davis et al. (2011) brought brings a counterfactual definition of a traffic conflict understood noted by according to Amundsen and Hydén who wrote in the proceedings of the 1st Workshop on that a traffic conflict is in Oslo: as "…an observable situation in which two or more road users approach each other in space and time to such an extent that *there is a risk of collision if their movements remain unchanged*." Applying the work on causality by Pearl (2009), Davis et al. developed a causal concept that connected conflicts and crashes via the commonalty of their initial conditions and contributing factors.

Recently, Tarko (2018) continued the work initiated by Davis et al. on counterfactual approach to traffic conflicts by narrowing the space of traffic conflicts. This change can be summarized with the following modified version of the 1977 definition: "…an observable situation in which two or more road users approach each other in space and time to such an extent that *the separation between involved road users is unacceptable and collision occurs* if their movements remain unchanged." According to this modified concept, a traffic conflict is unintentional and collision can be avoided only by executing a successful evasive maneuver. The evasive maneuver is delayed by a random amount of time. Tarko (2018) demonstrated that response delay in heterogeneous conditions follows the Lomax distribution. The Lomax distribution – a special case of the Generalized Pareto distribution – is justified with the data generating mechanism. Unlike the extreme value theory and its statistics, the new approach allows formulating specific and verifiable conditions of the results validity.

The primary objective of the paper is to confirm that the properties of the estimates derived from the theory are indeed observed in the obtained results. This confirmation would support the claim that the method is valid. The secondary objective is to demonstrate the method versatility and adaptability by applying it to road near-departures where crash nearness is represented by a spatial and not temporal measure. First, the paper presents and discusses the theory and the behavior of the results anticipated from the theory. Then, the study is shortly presented and the results behavior examined and compared to test the method validity.

2. Failure-based traffic events

Most of the existing traffic conflict concepts follow the established practice and research and they do not stress a failure as a necessary condition. One may justify this approach as practical since the current observation practice does not allow in most cases making distinction between interactions caused by failure from those caused by aggressive behavior. Tarko (2018) analyzed the estimation consequences of including failure-free aggressive interactions among claimed conflicts to find out that this practice may lead to a great overestimation of the expected number of crashes. Although a regression analysis that uses claimed conflicts and reported crashes overcomes this problem by forcing the model to follow the observed crash counts, it is accomplished at the risk of following the spurious association at expense of the causality. This shift undermines the usefulness of the analysis in investigating the safety factors on the top of the other weaknesses of the crash-based estimation already mentioned.

2.1. Theory

Let S_c be threshold separation (in time or distance) between two road users sufficiently short to claim that it is not acceptable to the involved road users. Consequently, a traffic interaction may be claimed a conflict caused by a failure if the observed shortest separation S_m during the interaction is shorter than S_c. Exponentially distributed random response delay $x = S_c - S_m$ constitutes a simple survival model with the probability of crash $P(C|N) = \exp(-rS_c)$, where r is the response rate.

Response rate r varies independently from one conflict to another. The multiplicity of independent factors and the central limit theorem would point out to the normal distribution as a reasonable choice for response rate r of the rate could take any value. The non-negativity of rate r justifies the Gamma distribution as a plausible alternative. After all, the Gamma distribution well approximates the normal distribution if the mean is sufficiently larger than the standard deviation and it is assumed for crash rates at individual roads in Negative Binomial regression models. These models have become the most common type in safety analysis of heterogeneous crash frequencies (Lord and Mannering, 2010). The Gamma-mix of exponential distributions is equivalent to the Lomax distribution (Lomax, 1954; Tarko, 2018). Since crash occurs when response delay x is longer than threshold separation S_c, the probability of crash can be estimated as:

$$P(C|N, S_c) = 1 - F(X \leq S_c) = (1 + \theta S_c)^{-k} \tag{1}$$

where $P(C|N,S_c)$ stands for probability of crash C when separation S reaches threshold separation S_c and near crash N is still in progress, θ and k are parameters of both the Gamma distribution of response rate r and the Lomax distribution of response delay X. The expected number of crashes during the period with n traffic conflicts is:

$$Q_C = n \cdot P(C|N, S_c) = n \cdot (1 + \theta S_c)^{-k} \tag{2}$$

The details of the theory and estimation method can be found in (Tarko, 2018). The critically important property of conflicts-based estimates of crash frequency is the estimates' insensitivity to a sufficiently short separation threshold used to claim traffic conflicts. This is shown in Eq. (3) for appropriate separation threshold S_o and even shorter threshold $S_c = S_o - \delta$.

$$n_c \cdot P(C|N, S_c) = n_c \cdot [1 + \theta_c S_c]^{-k}$$

$$n_c \cdot P(C|N, S_c) = n_o \cdot (1 + \theta_o \delta)^{-k} \cdot \left[1 + \frac{\theta_o}{1 + \theta_o \delta}(S_o - \delta)\right]^{-k}$$

$$n_c \cdot P(C|N, S_c) = n_o \cdot (1 + \theta_o S_o)^{-k}$$

$$n_c \cdot P(C|N, S_c) = n_o \cdot P(C|N, S_o) \tag{3}$$

Thus, the assumption of a failure with random response implies that the expected number of crashes is estimated correctly regardless of the assumed S_c threshold as long as the threshold used to claim conflicts is sufficiently short to be uncomfortable to the road users involved in all the claimed conflicts. Too long threshold used to claim conflicts leads to false positives that inflates the number of conflicts and causes overestimation of the expected number of crashes (Fig. 2). It should be noted that the opposite situation of a very short threshold causes missing some true conflicts (false negatives) but this undercounting of conflicts is fully compensated with the increase in the probability of crash $P(C|N)$. Although the estimation based on unnecessarily short separation thresholds produces unbiased results, the estimation efficiency is reduced due to the data underutilization. Thus, the largest separation threshold within the range of stable estimates is the best choice. The objective of the following example is to check if indeed the crash estimates behave as prescribed by the theory.

There are several advantages of the proposed method. The sensitivity of the expected crash count estimates to the choice of separation threshold S_c is eliminated by selecting the proper threshold. This is also the way to eliminate the arbitrary choice and to avoid the estimation bias. The extreme and exceedance methods are justified purely based on the statistical ground and the extreme value theory. According to extreme value theory, an accuracy is guaranteed by the asymptotic properties of distribution tails. Thus, the smaller is the threshold, the higher is the chance of an accurate estimate. Derivation of the Lomax distribution from the plausible conceptualization of traffic conflicts guarantees the validity of the estimation for the entire range of the distribution as long as the assumptions are met. These assumptions are rooted in the phenomenon itself and can be checked in the field. Finally, the extreme value theory is valid if the observations can be assumed independently and identically distributed. In the proposed Lomax-based method, a single distribution of response delays is derived for heterogeneous conditions represented by gamma distribution – the distribution already proven sufficient for representing heterogeneity of crash counts in Negative Binomial models. Independence of traffic conflicts is accomplished with a sufficient separation of the events in time and space. In fact, the modified definition of traffic conflicts calls for more severe conflicts, thus less frequent and more isolated from each other, than in the current practice.

2.2. Estimation of the Lomax parameters and crash frequency

The Lomax distribution of response delay x that supports Eq. (1) is: $1 - F(x) = (1 + \theta x)^{-k}$. The logarithm of both the equation sides gives a linear log-log relationship: $-\log(1 - F(x)) = k \cdot \log(1 + \theta x)$. This property and the typically low sensitivity of the MLE around the solution allowed proposing a simple single-parameter estimation (SPE) method of estimating the Lomax parameters by setting $\theta = 1/S_c$ and computing k as (Tarko, 2018):

$$\hat{k} = \frac{-\sum_{i=1}^{n} \log(1 - (i - 0.5)/n)\log(1 + x_i/S_c)}{\sum_{i=1}^{n} [\log(1 + x_i/S_c)]^2} \tag{4}$$

where:

S_c = threshold separation,

$x_i = S_c - S_{mi}$ is the ith response delay ordered from the smallest value x_1 to the largest value x_n,

n = number of traffic conflicts and crashes during the observation period.

A crash occurs when the response delay x is longer than S_c. Since the response delay cannot be observed at crash, it is assumed to be equal to S_c. Setting $\theta = 1/S_c$ in Eq. (2) produces the equation for the expected number of crashes during the period with observed n conflicts as follows:

$$Q_C = n \cdot P(C|N)$$

$$Q_C = n \cdot 2^{-\hat{k}} \tag{5}$$

where:

Q_C = expected number of crashes,

$P(C|N)$ = probability of crash (or crash/conflict ratio),

n = number of observed traffic conflicts and crashes,

$\hat{k}$ = parameter k estimated with Eq. (4).

Table 1 provides example data for twenty traffic conflicts observed with the time to collision shorter than 2 s. The second column includes the observed separations sorted from the largest to the smallest. The remaining columns present: response delay x, corresponding delay quantiles, and the logarithm values included in Eq. (4). The sums at the bottom of columns $L_1 \bullet L_2$ and $L_2 \bullet L_2$ are the numerator and denominator in Eq. (4), respectively. The calculations with Eqs. (4) and (5) are presented below.

$$\hat{k} = \frac{-\sum_{i=1}^{n} \log(1 - (i - 0.5)/n)\log(1 + x_i/S_c)}{\sum_{i=1}^{n} [\log(1 + x_i/S_c)]^2} = \frac{0.9387}{0.1311} = 7.162$$

$$Q_C = n \cdot P(C|N) = n \cdot 2^{-\hat{k}} = 20 \cdot 2^{-7.162} = 0.140$$

In the Lomax distribution, the average response rate is $\bar{r} = k\theta = 7.162 \cdot (1/2) = 3.58$ and the average response time is

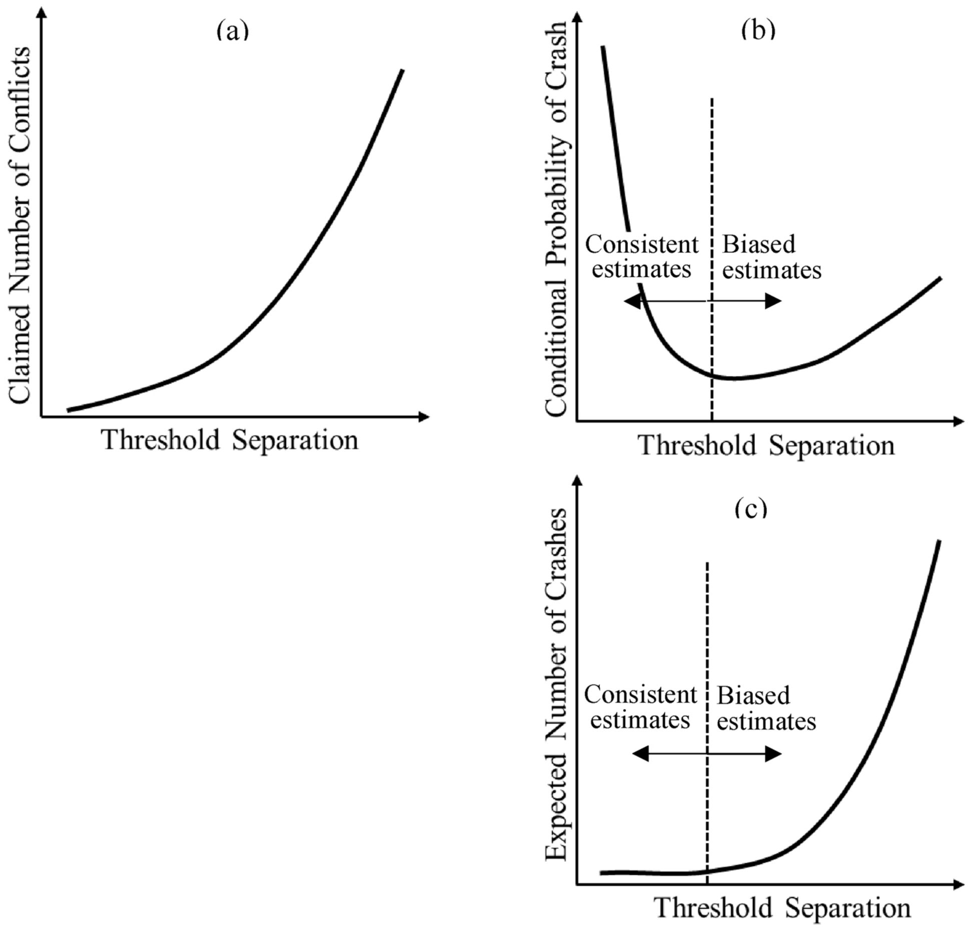

Fig. 2. The effect of threshold separation on: (a) the number of claimed traffic conflicts, (b) the estimate of the conditional probability of crash given conflict.

Table 1
Intermediate results in the example calculation of the expected number of crashes (S_c = 2 s).

I	Separation S	x	$F(x) = (i - 0.5)/n$	$L_1 = \log(1 - F(x))$	$L_2 = \log(1 + x/S_c)$	$L_1{\cdot}L_2$	$L_2{\cdot}L_2$
1	1.99	0.01	0.025	−0.0110	0.0013	0.0000	0.0000
2	1.97	0.03	0.075	−0.0339	0.0065	−0.0002	0.0000
3	1.94	0.06	0.125	−0.0580	0.0120	−0.0007	0.0001
4	1.93	0.07	0.175	−0.0835	0.0157	−0.0013	0.0002
5	1.92	0.08	0.225	−0.1107	0.0164	−0.0018	0.0003
6	1.90	0.10	0.275	−0.1397	0.0212	−0.0030	0.0005
7	1.87	0.13	0.325	−0.1707	0.0280	−0.0048	0.0008
8	1.86	0.14	0.375	−0.2041	0.0285	−0.0058	0.0008
9	1.84	0.16	0.425	−0.2403	0.0341	−0.0082	0.0012
10	1.81	0.19	0.475	−0.2798	0.0386	−0.0108	0.0015
11	1.77	0.23	0.525	−0.3233	0.0468	−0.0151	0.0022
12	1.77	0.23	0.575	−0.3716	0.0470	−0.0175	0.0022
13	1.77	0.23	0.625	−0.4260	0.0478	−0.0203	0.0023
14	1.74	0.26	0.675	−0.4881	0.0529	−0.0258	0.0028
15	1.71	0.29	0.725	−0.5607	0.0594	−0.0333	0.0035
16	1.62	0.38	0.775	−0.6478	0.0758	−0.0491	0.0057
17	1.57	0.43	0.825	−0.7570	0.0854	−0.0647	0.0073
18	1.48	0.52	0.875	−0.9031	0.0997	−0.0900	0.0099
19	1.04	0.96	0.925	−1.1249	0.1696	−0.1908	0.0288
n = 20	0.47	1.53	0.975	−1.6021	0.2468	−0.3955	0.0609
					Sum	−0.9387	0.1311

$1/\bar{r} = 1/3.58 = 0.28$ s. The variance of the response rate $\mathrm{var}\, r = k\theta^2 = 7.162{\cdot}(1/2)^2 = 1.79$ indicates quite considerable unexplained heterogeneity.

2.3. Driving simulator experiments

The expected behavior of estimates briefly presented in the previous sections is checked by applying the method to road near-departure data collected in a driving simulator. Although a road departure is not a crash, it is a rare event and if it occurs, it frequently causes injuries and damages. In lieu of actual departures, lane-keeping performance was investigated in driving simulators in the past (Akerstedt et al., 2005; Auberlet et al., 2010; McLane and Wierwille, 1975) by studying the variability of the lateral position of vehicles. This approach does not distinguish between aggressive behavior while well controlling the lateral position and driving too closely to the road edge due to driver's error. Although aggressive behavior may contribute to the risk of road departure, its causal connection with an actual departure is much weaker than an unintentional violation of the driver-accepted minimum lateral clearance.

The original research objective of the simulation experiments was to analyze the evolution of the behavior and performance of drivers who are exposed to runs repeated daily on the same road and in the same simulator (car) for a prolonged period (Sandstrom, 2009). Although the original objective was interesting and worthy of exploration, the main purpose of this analysis is to demonstrate the usefulness of the Lomax-based method. Four participants left the road accidentally only four times during the entire data collection period. The low number of departures did not provide a sufficient basis for estimating the departure risk for individual drivers and for investigating the risk changes during the study period. Therefore, near-departure events are used instead. A near-departure is first defined and then extracted from the data obtained in the experiments. Next, the proposed method is applied to estimate the expected numbers of departures for the four drivers in the

Fig. 3. Example renderings (left figure) and horizontal alignment (right figure) of the simulated road with the Freespace simulator.

first half and in the second half of the runs. Details are presented for a selected driver and then, all the results are summarized and discussed.

The Purdue University Freespace driving simulator was built in 2002 as a fixed-base installation. It included three 8 ft × 8 ft projection screens, a raised platform with a steering wheel and pedal assembly and a seat. The 3D effect was achieved with multiple projectors with polarized lenses and 3D glasses. The simulated road was rendered with a computer-generated images composed of elements selected from a catalog of topography, landscapes, cars, and road components (Fig. 3). The simulated road was 26.7 miles long with four 12-ft lanes wide divided by a 26-ft wide median. The shoulders were deliberately narrow (4 ft) and without guardrails in order to add difficulty to staying in the travelled way).

A limited number of human subjects were driving on the same road segment in the simulator repeatedly over an extended period to estimate the road and simulator familiarity on their safety-related performance. This experimental design served better the research objectives than a large number of subjects driving only a limited number of times. Four subjects included two female and two male Purdue students of age between 22 and 24. Three subjects participated in 19 runs and one subject in 20 runs. The runs scheduled after classes and before leaving for home created conditions that encouraged the subjects to drive reasonably fast to save time. The subjects were instructed to drive in the right lane at their comfortable speeds. They were advised about two types of crashes possible during the experiment: (1) being hit by a vehicle in the left lane and (2) crashing on the roadside if a tire left the travelled way.

2.4. Near-departures analysis

The proposed framework based on the Lomax distribution is applied to lane-keeping behavior to test the anticipated patterns in the results. The expected number of near-departures Q_N are connected with the expected number of departures Q_D and the conditional probability of departure $P(D|N)$ as follows:

$$Q_D = P(D|N) \cdot Q_N \tag{1}$$

Unlike in the presented example in Table 1, where time to collision was used to measure separation, this analysis uses lateral distance S_c between a tire and a paved area edge (shoulder edge). The research objectives, the simulator, and the experiment design conducted by Sandstrom (2009) are described first. Then, the proposed Lomax-based method is applied and the obtained results are discussed and summarized.

2.5. Definition of near departure

The lateral distance of the lead tire to the edge of a travelled way (lateral clearance) was a measure of the nearness to road departure. The travelled way includes the traffic lanes and a well-maintained paved shoulder that allows safe movement at a design speed. A departure occurred during the experiment when the lead tire crossed the outer edge of the right shoulder. Driving restricted to the right lane made departure to the left unlikely.

The initial threshold clearance to the road pavement edge was assumed to be 4 ft, which was the width of the shoulder. Violating this threshold clearance constituted a near-departure. Road departure was represented with zero or negative lateral clearance. For each driver, the expected frequency of departures was estimated first for the threshold of 4 ft and then repeated for other thresholds gradually reduced until the sequence of the estimates stabilized. In some cases, the estimation was terminated due to the number of near-departures became less than 10. If the theory worked and indeed the expected pattern in the results were observed, then the largest threshold beyond which the estimates stabilized would be most suitable for estimating the expected frequency of departures.

Fig. 4 presents the example near-departures. A near-departure event occurs when the lateral clearance remains smaller than the S_C threshold (for example, 4 feet). The smallest lateral clearance reached during a near-departure events represents the departure nearness for this event.

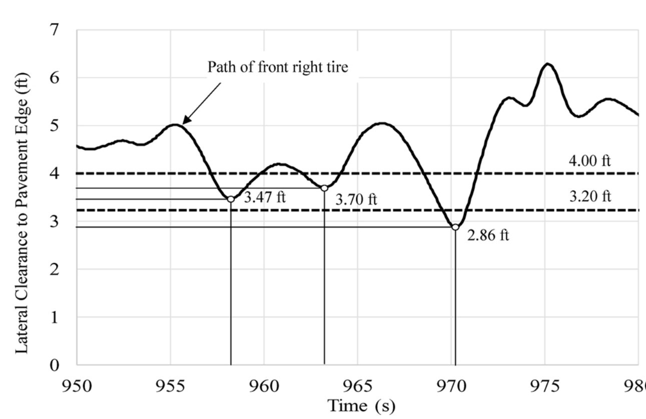

Fig. 4. Example near-departures defined with the 3.2-ft and 4-ft threshold clearance.

Thus, the reduction from the threshold clearance to the smallest clearance is utilized by the subject to realize the hazard and to initiate and execute the evasion action. This distance is the response delay x, which is calculated as the threshold clearance minus the smallest clearance during the near-departure event (Fig. 4).

Between the 955th and 975th seconds of the run and with the assumed 4-ft threshold clearance, there were three near-departures with the smallest clearances of 3.47, 3.70, and 2.86 ft. The corresponding response delays (0.53, 0.30, and 1.14 ft) were obtained by subtracting the smallest clearances from the 4-ft threshold. Applying the 3.20-ft threshold clearance reduced the number of near-departures during the considered 20 s to one near-departure with the response delay $3.20 - 2.86 = 0.34$ ft.

3. Results and discussion

The Lomax-based analysis was applied to eight sequences of lateral clearances obtained for the four subjects whose simulation runs were divided into two sequences. The single-parameter estimation method (SPE) was applied to estimate the k parameter with an assumed $\theta = 1/S_c$, where S_c is the threshold clearance.

Fig. 5 presents example results for subject 385 who drove the simulated road segment 10 times. Subject 385 and her ten runs were selected for the subject's unusually poor performance during these runs. It resulted in two departures while none of the other subjects left the road even once during their drives. The number of claimed near-departures was obviously declining with the decrease of the clearance threshold. The conditional probability of departure associated with a near departure was growing as expected with the decreasing threshold once the first proper threshold of 3.0 feet (sufficiently short) was reached. Until

reaching this threshold, however, the near-departures with clearance between 3 and 4 feet were associated with similar probability of departure and without any obvious trend. This rather surprising result may be justified with the initial driving poorly controlled by the subject and with the learning period during which the subject had been improving her driving skills. Since the probability of departure started growing with the reduction in the lateral clearance below 3 feet, the corresponding expected number of departures estimated based on claimed near-departures became insensitive to the further decreasing thresholds. This result is highly desired and, according to the theory, these estimates may be considered unbiased. It is worth to point out that the estimates are close to value 1 which is unusually high but reasonable given the two occurred departures.

During the initial ten runs, subject 385 improved her performance to the level comparable to other best performers in the study. This can be concluded based on the results obtained for the following $11-19$ simulation runs and presented Fig. 6. All the results exhibit the patterns implied by the theory. The conditional probability of departure is declining up to the threshold value of 3.4 ft and then it increases. Consistently, the estimates of the expected number of departures stabilize for the clearance thresholds 3.4 ft and smaller. The flat profile is subject to random fluctuations due to the limited number of observations. It is easy to point out the threshold of 3.4 ft as the largest among all the proper thresholds with the estimated number of departures during the 9 runs equals to 0.0034. All the results obtained for the suitable thresholds are marked with enlarged filled circles in both the figures.

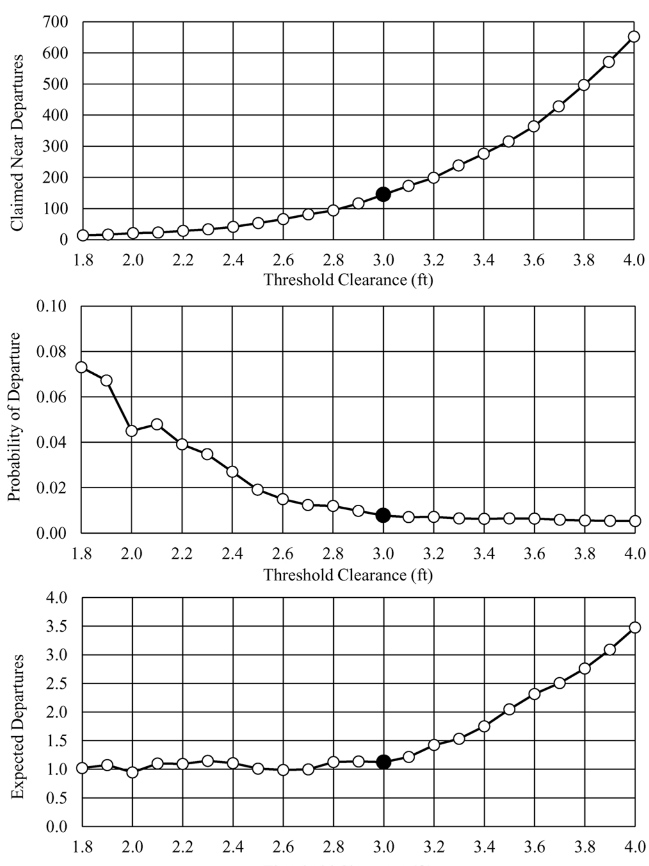

Fig. 5. Results for subject 385 and runs 1–10: upper figure – number of claimed near-departures, middle figure – conditional probability of departure during a near-departure, bottom figure: estimated expected number of departures during the ten runs.

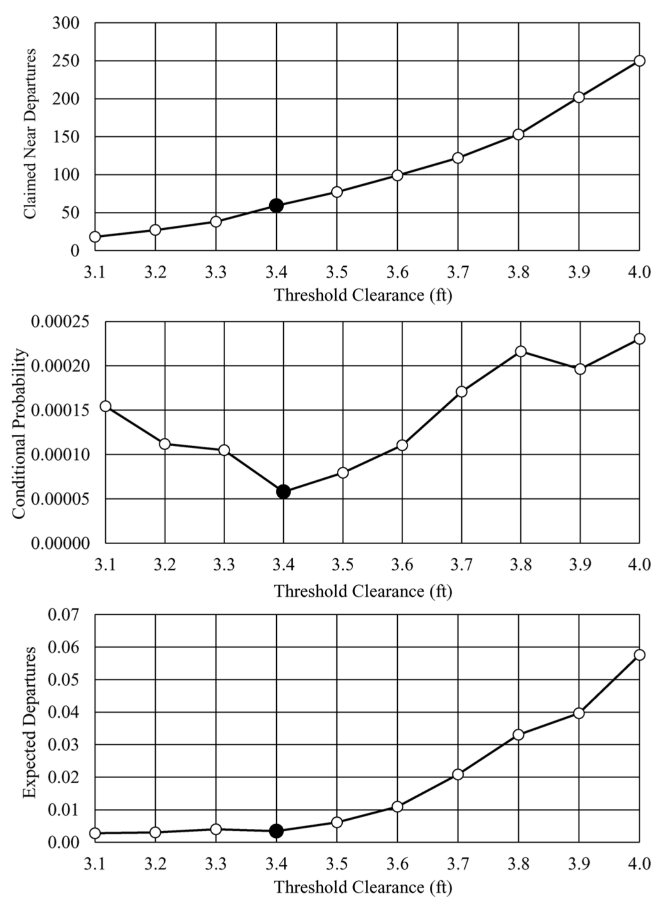

Fig. 6. Results for subject 385 and runs 11–19: upper figure – number of claimed near-departures, middle figure – conditional probability of departure during a near-departure, bottom figure: estimated expected number of departures during the nine runs.

Table 2
Expected number of crashes estimated based on near-departures claimed under selected thresholds for the four subjects and all sequences of runs.

Subject	Gender	Runs	Observed departures	Lateral threshold[a] (ft)	Claimed number of near-departures	Parameter k estimate	Conditional probability of departure	Expected number of departures	Miles between departures (1000s)
028	Male	1 – 9	0	3.7	56	11.51	0.0003424	0.0192	12.5
		11 – 20	0	3.7	92	15.05	0.0000294	0.0027	98.8
219	Male	1 – 10	0	3.3	43	10.54	0.0006732	0.0289	9.2
		11 – 19	0	2.0	19	6.26	0.0130344	0.2477	1.0
385	Female	1 – 10	2	3.0	143	7.01	0.0077455	1.1231	0.2
		11 – 19	0	3.4	59	14.08	0.0000579	0.0034	70.4
756	Female	1 – 10	0	1.7	13	5.54	0.0214568	0.2789	1.0
		11 – 20	0	3.1	53	13.16	0.0001096	0.0058	46.0

[a] Selected lateral thresholds are marked in Figs. 6–11 with enlarged filled circles.

Table 2 presents the results obtained for all the four subjects and two sequences of runs for each subject. Subject 028 was an experienced user of the driving simulator. He was involved in an intensive testing of the installation by driving the experimental road section numerous times and providing feedback. It is not surprising that his behavior and performance during the actual experiments were good and more consistent than other subjects. The threshold clearance of subject 028 was the same in both the sequences and the ability to recover from a near-departure event high as demonstrated with the low conditional probabilities of departure. The results obtained for Subject 028 emphasize the benefit of using jointly conflicts and probability of crash given a conflict. If one evaluates the safety performance only on the number of near-departures, the conclusion would be that the subject's performance was better during the first sequence with 56 near-departures compared to 92 near-departures in the second sequence. However, the expected distance between departures was over eight times longer during the second sequence of runs than the first sequence (98.8 miles compared to 12.5 miles). This improvement was thanks to a much lower conditional probability of departure that indicates the improved recovery skills slightly offset with the reduced attention leading to more frequent near-departures. By the way, this result is consistent with the risk perception and compensation hypotheses discussed widely in the literature.

The performance of male subject 219 was comparable to the performance of subject 028 during the first sequence of runs. Then, the speed of subject 219 and the number of near-departures started growing considerably in the second sequence of runs. The likely reduced attention led to the increase of number of near-departures at 3.3-foot threshold from 43 to 236. As the result of accepting lower lateral clearance to the road edge, the threshold reduced from 3.3 ft to 2.0 ft. The expected distance between departures decreased from already short to only 1 mile. This growing aggressive behavior was an exception among the subjects. All others improved their performance in the course of the experiments. One of the factors encouraging subject 219 to drive aggressively was no departure experienced by this subject during the experiments. This outcome was quite possible given that the probability of avoiding departure along the entire distance travelled in the simulator was around 0.75 for this subject in spite of the worsened behavior and performance.

Subjects 385 has already been discussed and her results will be only briefly summarized for the completeness of this overview. The subject performed poorly during the first sequence of runs with many near-departures and two road departures. However, in spite of the initial bad experience (are because of it), the subject improved her performance in the second sequence of runs. The expected number of departures in the second sequence was the second lowest among all the subjects in all runs.

Subject 756 had an experience similar to subject 385 by starting with rather poor performance, although without departures, and then by improving the performance considerably in the second sequence. In summary, three subjects improved their safety performance between the first and the second sequence of runs while one of the subjects started driving more aggressively and performed poorer in the second sequence of experiments.

In summary, the Lomax-based analysis identified three subjects who improved their safety performance by repeating runs in the same road segment. One female driver exhibited extremely poor performance but improved her skills fast to the level of becoming the safest driver. On the other hand, one male subject exhibited declining safety performance associated with reckless behavior and increasingly high speed. Although the small number of subjects did not allow generalization of the finding, it was clear that the subjects exhibited strongly diverse both driving skills and ability to improve or maintain their performance. The probability of departure conditioned on near-departure varied in some cases strongly, thereby indicating that the sole use of the frequency of near-departures to estimate safety is insufficient and it must be supplemented with the conditional probability of departure.

Based on the current understanding of driver behavior, it can be expected that a safe roadside with flat slopes and free of dangerous obstructions may prompt drivers to be less vigilant and drive closer to the paved travelled way. This would result in more frequent near-departures and higher conditional probability of a departure. This mechanism is similar to the observed effect of the increased self-confidence of the male driver who did not experience any departures during the experiments. Estimating such safety effects requires a proper experimental design or advanced statistical analysis of safety effects.

4. Closure

The Lomax-based analysis of safety-relevant events with the SPE method of estimating the probability of crash (here road departure) was found to be efficient in estimating the expected number of road departures. This efficiency was demonstrated with stable estimates of the crash probability even for a relatively small number of claimed conflicts.

The results of the analysis closely followed the trends prompted by the theory. The most encouraging is the convergence of the estimated expected number of crashes for threshold separation (lateral clearance) below a certain value. Although the convergence point is easy to identify in most cases, there is a need for a formal test and method of determining such a point to eliminate subjectivity.

The results confirm that the number of traffic conflicts carry safety information. Nevertheless, converting the conflicts into crashes requires the probability of crash conditioned on a conflict. Thus, the expected numbers of crashes (departures in the presented example) must be estimated as the product of the number of conflicts and the probability of crash estimated at the threshold nearness to crash.

The proposed theory and its counterpart – estimation method – assumes failure as the necessary condition of claiming a traffic conflict. Although this assumption requires conservatively small threshold separations and longer observation periods, the upside is the simplicity and intuitiveness of the concept leading to practical method of estimation and convincing interpretation of the results.

The required longer observation periods may not be a big hurdle when efficient and accurate techniques of observing traffic conflicts are developed and implemented. Autonomous vehicles that acquire and utilize safety-relevant data for efficient and safe autonomous navigation are supposed to preserve near-crash and crash data for post-event inspection.

More studies are needed to build further confidence towards the proposed failure-based traffic conflicts method. One of the available opportunities is provided by naturalistic driving studies that deliver traffic conflicts and collisions for the same observation period. The already mentioned opportunity provided by emerging autonomous vehicles is quite a realistic expectation which emphasizes the importance of collecting and sharing such data for improving safety on public roads with presence of new generation vehicles.

Author's statement

Andrew Tarko: Ideas and concepts; development of methodology; creation of models; verification; application of statistics, conducting research, processing data, writing draft and final paper.

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.

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