

CALCULATION OF THE POINT OF NO RETURN (PONR) FROM REAL-WORLD ACCIDENTS

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ABSTRACT

Continuing efforts in the field of traffic accident research has led to the development of various active and passive safety systems. They act and influence an incident/accident at different points in time in order to mitigate or avoid a collision. In the event of a collision, the decision to deploy passive safety systems must be made quickly, as the typical activation time is between 10 to 40 ms after the initial contact. However, for future interior/seating concepts and earlier deployment times of restraint systems it is necessary to predict an unavoidable collision much earlier. As the knowledge about this so-called Point Of No Return (PONR) is crucial, this paper introduces an approach to calculate it through using numerical simulation.

This paper uses real world accidents out of the GIDAS (German In-Depth Accident Study) project. The database contains more than 33.000 accidents with personal damage. The reconstruction of the several phases (normal driving, critical situation, pre-crash, in-crash, post-crash) is the basis for the estimation. Therefore, an imminent collision is predicted by simulating the vehicle's possible behavior using a multi body system. If any physically possible vehicle reaction exists that leads to an avoidance of the collision, the PONR has not yet been reached. If all simulation solutions would lead to a collision, the calculations must go one time step backwards. Through an efficient iterative approximation procedure the PONR can be found in a reasonable number of iterations. The approach focuses on the maxima in longitudinal direction (full acceleration or deceleration), in lateral direction (full steering right or left) and in all four combinations of steering and accelerating/decelerating.

The approach can be generally used for all collision types. Here, it is applied to rear-end collisions between two vehicles, highlighting the potential of different avoidance strategies like full deceleration or full steering as a function of time. The distribution of time across all PONRs shows that passive safety measures can be activated prior to the collision in the vast majority of cases. Therefore, occupant protection can be further improved and accidents consequences could be mitigated to a higher degree.

The suggested approach can estimate the PONR for real accidents. An adaption to naturalistic driving data as well as real time estimation is conceivable. This would signify a crucial contribution to the current research on the distinction between accidents and incidents. However, some adaptations would be necessary to enable such calculations. The current simulations are based on idealized acceleration/deceleration and steering behavior, while traffic flow is neglected. Both simplifications lead to an underestimation of the PONR. As the approach is modularized, it can be further developed towards other vehicle behavior maneuvers, specific driver models, or interactions with Advanced Driver Assistance Systems (ADAS).

The PONR is an important value for improved vehicle safety. The developed approach allows to estimate the further potential of passive safety systems with regard to earlier activation times. Furthermore, it can be used to evaluate collision avoidance strategies and to parameterize ADAS.

MOTIVATION AND OBJECTIVE

Traffic accident research and its influence on road safety

Traffic accident research is one of the most important aspects for to reduce road traffic accidents, casualties, fatalities, disabilities, and socio-economic costs. It aims to analyze the causes, sequences, and consequences of accidents; and provides evidence used for future regulations, approaches, technical and infrastructural measures.

Besides national statistics (typically based on sampled police data) in-depth accident investigations are essential to fully understand the accident scenario and to provide appropriate solutions. These initiatives collect as much evidence of accidents as possible to enable analysis of accident causes and to develop approaches for the future mitigation and avoidance of accidents. Collected in-depth accident data is an important source for engineers that aim to develop and improve safety systems. Existing safety measures (e.g. secondary safety measures like belts or airbags) can be further adjusted and optimized on the basis of retrospective data analysis. Additionally, future safety systems or measures and their associated potential benefit can be analyzed by prospective methods, e.g. by virtual simulations. The final goal is the avoidance of accidents. In the transition period, however, one important goal is the mitigation of accidents and the reduction of the consequences to the involved persons by means of integral safety measures. The success of these measures strongly depends on the reliable detection of forthcoming crash events.

Necessity and importance to predict an imminent collision more early

The certainty of an imminent collision as early as possible is very important for effective activation strategies for vehicle safety systems. Passive safety systems usually operate with activation times between 10 to 40 ms after initial contact. Active safety systems activate full when a situation is highly critical or just before a collision. The earlier a system has certainty about an imminent collision the better it can deploy and act without risking a false positive activation. The example of vehicle restraint systems show that an earlier activation can be used to distribute deceleration over a longer distance and to avoid peak loads on the human body. This would significantly contribute to the reduction of thorax and head injuries.

Unfortunately, there is a lack of information for traffic accidents. The need for a model to approximate the point in time, when all available measures must be used to reduce the consequences of a collision is very high. Not only for current vehicles (SAE level 0 to 2 [1]) but even more for vehicles with automated driving functions (SAE level 3 to 5 [1]) and new seat and/or interior concepts more time is crucial to prepare the vehicle and its occupants to an imminent collision.

METHODS AND DATA SOURCES

Point Of No Return (PONR)

The ACEA safety model generally describes a traffic accident in its five phases as seen in Figure 1. Between a critical event at t_{crit} and the collision at t_{coll} exists a theoretical point t_u where the collision is unavoidable. That means, that no reaction can prevent the imminent collision after this point in time (this does not mean that no mitigation is possible). This point represents the Point Of No Return (PONR). It is also known as CU-criterion [3] or time of unavoidability [5].

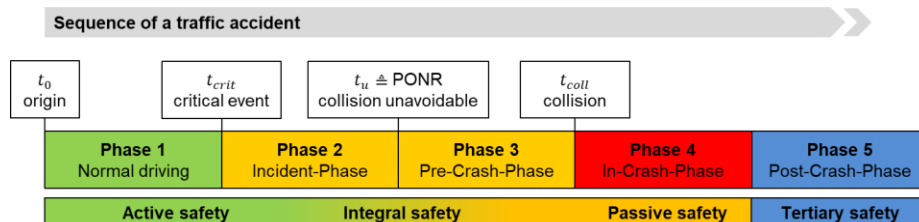


Figure 1. Sequence of a traffic accident based on the ACEA safety model [2]

Limit of vehicle dynamics

Critical events occur very often in road traffic. While most of the incidents return to normal driving states due to proper participant reactions or other influences, the rare case of an accident has led to a collision, as the participant(s) failed to avoid it. At some point earlier, there was the PONR, where the imminent collision is unavoidable through any vehicle behavior.

As the term unavoidable is a final state, the value of the PONR cannot be dependent on the actual or theoretical driver reactions nor on any specific safety system, but rather on physical constraints like the limit of vehicle dynamics. In the case of ground bound vehicles like passenger cars this is mainly the tire-road friction and its transferable force limits as described by the circle of forces (also known as Kamm's Circle) [3], [4]. Figure 2 shows the circle of forces and the vehicle maneuvers model described in the next paragraph. Equation 1 and 2 gives the force and acceleration distribution.

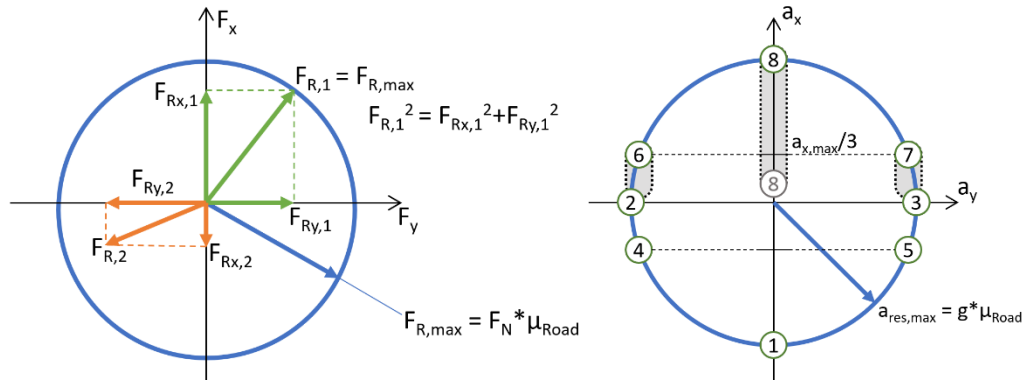


Figure 2. Circle of forces, separation of longitudinal and lateral forces and vehicle maneuvers

$$F_R = \sqrt{F_{Rx}^2 + F_{Ry}^2} \text{ (Equation 1)}$$

$$a_{xy} = \mu_{road} \cdot g = \sqrt{a_x^2 + a_y^2} \text{ (Equation 2)}$$

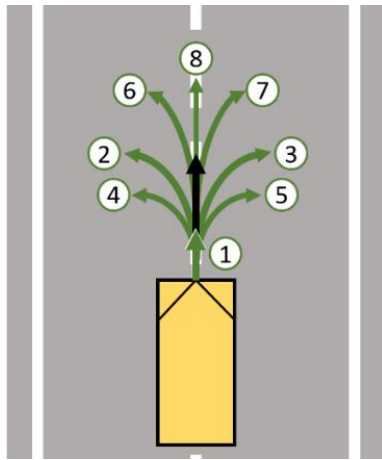
Model for vehicle maneuvers

Unfortunately, the PONR is not measurable and unknown for traffic accidents. There are several model based approaches to approximate vehicle behavior, where especially [6], [7] and [8] must be mentioned. All of these approaches determine the PONR prospectively for idealized situations and cannot be applied directly to real accidents. To determine the PONR for real accidents the development of an advanced model is necessary, taking into consideration the theoretical approaches.

The approach developed for this paper models eight vehicle maneuvers shown in Figure 3, that are able to affect a traffic situation.

In contrast to idealized, generic situations considered in the present approaches (see above), the real situation is a very complex one, including multiple participants, vehicle dynamics, environmental objects and others. Additionally the consideration is a posteriori, as the situation has already taken place. To consider the reactions of the drivers in the actual situation it is necessary to oversteer the reconstructed vehicle behavior with respect to the modeled one at a specific time before the collision. The first point in time when oversteering leads to a collision for all behaviors represents the PONR. This boundary value problem cannot be solved analytically anymore. In contrast, numerical

simulation with a Multi Body System (MBS) is able to solve such a problem, however it is slower and more inaccurate. This paper uses the IPG Carmaker [9]. The variation of the initial vehicle behavior in the accident with the eight modelled ones at specific times is implemented in the simulation environment in Matlab / Simulink [10], [11]



- 1) longitudinal maximum (full deceleration)
- 2) lateral maximum (steering left)
- 3) lateral minimum (steering right)
- 4) longitudinal min – lateral max combination (deceleration and steering left)
- 5) longitudinal min – lateral min combination (deceleration and steering right)
- 6) longitudinal max – lateral max combination (acceleration and steering left)
- 7) longitudinal max – lateral min combination (acceleration and steering right)
- 8) longitudinal minimum (full acceleration)

Figure 3. Model for vehicle maneuvers to affect a traffic situation or accident

The maneuvers are parametrized with the help of the accident reconstruction. The full acceleration and deceleration use the maximum available grip level on the specific road condition (surface, humidity, pollution etc.) and the extrema of the specific vehicle model (engine characteristics, gearbox and current gear, braking system) which is used in the simulation. The steering behavior is simplified by a clothoid with a constant steering angle velocity of $360^\circ/s$, so there is no unit-impulse-sequence but a very severe evasion maneuver. The combination maneuvers split the transferable force into longitudinal and lateral direction in reference to Equation 2 in the proportions given in Equation 3 and 4. Therefore, the maneuver uses a significant steering angle and still has a strong longitudinal deceleration / acceleration.

$$a_x = \frac{1}{3} \mu_{road} \cdot g \text{ (Equation 3)}$$

$$a_y = \sqrt{(\mu_{road} \cdot g)^2 - (a_x)^2} \approx 0.943 \cdot \mu_{road} \cdot g \text{ (Equation 4)}$$

Furthermore, the model contains some uncertainties and a systematic overestimation of vehicle possibilities. This leads to an underestimation of the PONR (meaning it might be closer to t_0) and is addressed in the limitations paragraph.

Approximation method and simulation time efficiency

As already mentioned the PONR is unknown for real-world accidents and there is only the known constraint that it is located before the collision. Considering the criticality of a situation according to [14] as the risk as a function of time, Figure 4 shows that the PONR is the distinction (zero crossing) between a critical situation and an unavoidable collision event. Thereby the exact function is unknown and the approach does not consider the collision severity. To approximate the PONR to a certain precision dt , the model must apply at several time steps backwards from the point of the collision. At every time step there is a dynamics simulation run in forward direction, and the verification of a collision. This would result in a huge number of simulation runs, for what reason time efficient approximation methods are strongly required. Using common values, the simple example in Equation 5 illustrates this requirement, as a four-year calculation time is unacceptable.

$$\Delta t_{sim} = \Delta t_{single-sim} \cdot n_{mnrv} \cdot \frac{\Delta t_{acc}}{dt} \cdot N_{sample} \approx 4.28 \text{ years (Equation 5)}$$

with

Δt_{sim}	Duration of the entire PONR calculation for the sample
$\Delta t_{single-sim}$	Duration of a single simulation run; assumption: $\Delta t_{single-sim} = 30 \text{ s}$
n_{mnrv}	Number of maneuver plus initial simulation; model: $n_{mnrv} = 9$
Δt_{acc}	Duration of the accident simulation; usually: $\Delta t_{acc} \approx 5 \text{ s}$
dt	Step size (equivalent to PONR precision); assumption: $dt = 10 \text{ ms}$
N_{sample}	Sample size, number of accidents; assumption: $N_{sample} = 1000$

As the requirement for a time efficient simulation is very high, the model uses a combination of several methods. The following sub-paragraphs explain the three major approaches.

Order of avoidance maneuvers: If any maneuver is able to avoid a collision it is not important what the result of the other maneuvers is. As in this case at least one maneuver is able to avoid the collision, the approach obviously did not reach the PONR yet. Thereby the un-simulated maneuvers can be skipped and the simulation moves one time step closer to the collision (in contrast it is not clear if the PONR is already reached unless all maneuvers are not able to avoid a collision). Using this circumstance in combination with the knowledge of maneuver effectiveness from literature and traffic accident research, the model sorts the maneuvers in an efficient way (full braking first, evasion second, acceleration last etc.).

Bisection method: Approximation methods like the Newton's method [15] as well as the Regula-Falsi [15] and others would be promising to determine the described zero crossing. However, they cannot be applied directly as they require an analytical, differentiable function, which is not the case for the function in Figure 4. However, the bisection method [15] is a slower, but appropriate alternative to determine the PONR under these circumstances.

Generally, the bisection method divides the current time interval equally into two parts and verifies the function value. Here, function value means the determination of the collision or the avoidance. The described model uses the bisection method multiple times, so the step size dt_i decreases per iteration i according to Equation 6.

$$dt_i = \frac{\Delta t_{acc}}{2^i} \text{ (Equation 6)}$$

Starting with the duration of the initial accident simulation Δt_{acc} in the interval $[t_0, t_{coll}]$ leads to a necessary number of i iterations to reach a certain precision ε , see Equation 7.

$$i = \log_2 \left(\frac{\Delta t_{acc}}{\varepsilon} \right) \text{ (Equation 7)}$$

Using the bisection method solely and assuming typical values of $\Delta t_{acc} \approx 5 \text{ s}$ and $\varepsilon = 10 \text{ ms}$ leads to $i \approx 8.97$ meaning 9 iterations. The number of necessary iterations is unaffected by the exact position of the PONR within the entire interval $[t_0, t_{coll}]$.

Fixed step size: As accident investigation and especially its reconstruction shows, that the majority of the cases can be avoided by an emergency maneuver within one second before the collision, the model efficiency can be raised by using this knowledge to reduce the number of iterations. A preceding consideration with a fixed step size Δt_{fixed} can roughly determine the PONR position (see Figure 4, orange steps 1. and 2.). Afterwards the described bisection method applies multiple times in the corresponding one-second interval to determine the PONR more accurate (see Figure 4, green step 3.). Thereby the bisection method needs less iterations compared with application on the entire interval $[t_0, t_{coll}]$, see Equation 8.

$$i = i_{fixed} + \log_2 \left(\frac{\Delta t_{fixed}}{\varepsilon} \right) \text{ (Equation 8)}$$

Using a fixed step size $\Delta t_{fixed} = 1\text{ s}$ and a precision $\varepsilon = 10\text{ ms}$ is leading to $i = i_{fixed} + 6,64$ necessary iterations. Thereby, this combination reduces the number of iterations if the PONR is within the first second prior to the initial collision.

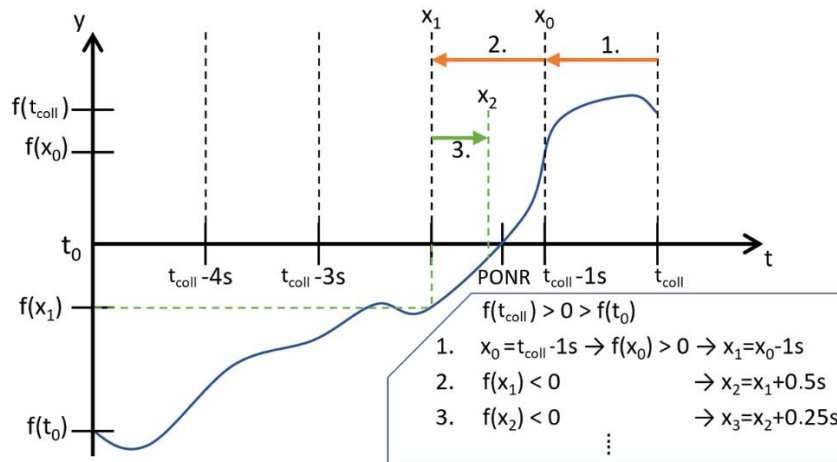


Figure 4. Combined approximation method of fixed step and bisection to determine the PONR

Therefore, a combined approximation method based on a fixed step size (see Figure 4, orange steps 1. and 2.) with a bisection method (see Figure 4, green step 3. multiple times) appears to be the most efficient for the introduced approach. According to reversed Equation 6, this is true for accident simulations with a duration $\Delta t_{acc} > 1.3\text{ s}$.

German In-Depth Accident Study (GIDAS database)

For the analysis accident data from the German In-Depth Accident Study (GIDAS) is used. GIDAS is the largest in-depth accident study in Germany. The data collected in the GIDAS project is very extensive, and serves as a basis of knowledge for different interest groups. Due to a well-defined statistical sampling plan, representative statements for the German accident scenario are possible. Since July 1999, the GIDAS project collects on-scene accident case information in the areas of Hanover and Dresden. GIDAS collects data from all kinds and types of accidents related to personal damage. Approx. 3.500 pieces of information (about vehicles, persons, injuries, infrastructure, environment etc.) are coded in the database per accident on average. Finally, every accident is also reconstructed.

The project is funded by the Federal Highway Research Institute (BAST) and The Research Association of Automotive Technology (FAT), a department of the German Association of the Automotive Industry (VDA). Use of the data is restricted to the participants of the project. However, to allow interested parties the direct use of the GIDAS data, several participation models exist. Further information can be found at www.gidas.org [12].

To ensure representative results, GIDAS data should be weighted towards the German national statistics. This is necessary due to slightly biased data. The investigation teams are not thoroughly informed about all accidents, information about injuries cannot always be obtained immediately and differences in the investigation areas cannot be excluded. The derived conclusions out of a study with weighted GIDAS data can be used for statements that can be considered as representative for the German accident scenario.

The GIDAS dataset is weighted towards the German national traffic accident statistics of the year 2016 on the basis of the parameters accident site (urban, rural), accident severity (accident with slightly, seriously, fatally injured persons) and type of accident (seven different categories).

RESULTS

The presented method of calculating the PONR should be applied to an example accident scenario to provide results out of real accidents. The aim is to use as many comparable accidents as possible to produce significant results. For

this reason, an accident scenario is chosen that frequently occurs in the area of personal injury accidents. The decision is made for rear-end collisions between two cars.

Relevance of rear-end collisions between two cars in German accidents with personal damage

In the first step, the GIDAS dataset (Effective December 31st, 2016) is filtered step by step to check the relevance of this accident scenario. One important filter criteria is the accident year. Here, only accidents of the years between 2005 and 2016 were used as the number and quality of information available in the GIDAS database increased significantly in 2005. Therefore, a total number of 20,148 reconstructed accidents are available as the basis (100 %) for the following analysis (see Figure 5). Next, three further filter steps are applied:

- accident with personal damage, involving at least one passenger car: 16,521 (82.0%)
- thereof: at least one collision between two cars: 6,091 (30.2%)
- thereof: rear-end collision (front of one car strikes preceding car at the back) 2,977 (14.8%)

Although accidents with personal damage are characterized by a tremendous variety in terms of involved road users, vehicle types and collision constellations, the group of “rear-end collisions between two cars” has a quite large relevance. More than every seventh accident with personal damage in Germany (in 2016) belongs to this group (see Figure 5).

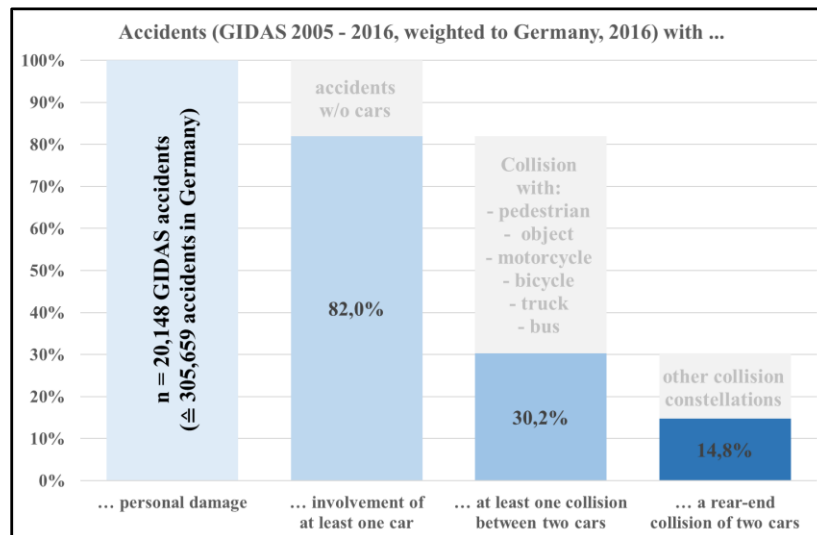


Figure 5. Relevance of rear-end collisions between two cars in German accidents with personal damage

In total, 2,977 GIDAS accidents (representing 45,159 accidents in Germany in 2016) are generally available for further analyses. However, the calculation of the PONR requires some more filtering. On the one hand, some reconstruction parameters are essential for the simulation. On the other hand, the considered accidents should be as similar as possible to the idealized scenario described in Figure 8. Thus, the following filter criteria are additionally used for the creation of the master dataset out of the GIDAS database (used GIDAS variables and codes in brackets):

- collision between participant 1 and 2 in the accident [BETNR < 3]
- first collision for both cars [NRKOLL = 1]
- rear vehicle had a front collision [VDI2 = 1]
- preceding vehicle had a rear end collision [VDI2 = 3]
- collision angle (angle between vehicle’s speed vectors) within $\pm 15^\circ$ [-15° ... KWINK ... 15°]
- no skidding or instable vehicle condition prior to the collision [SCHLEU = 2]
- known parameters: initial speed, braking deceleration and distance, collision speed, max. friction value

The filtering process results in 1,878 accidents that meet the above mentioned criteria. Out of these, 1,019 accidents have already been simulated and written into the 2016 Pre-Crash-Matrix (PCM) [13]. So, the basis for the calculation of the PONR are these 1,019 accidents between two cars with a rear-end collision resulting in personal damage

to at least one person. After weighting these accidents to the German national accident scenario of 2016, these accidents represent 1,261 accidents. This means that the considered accident scenario is slightly under-represented in GIDAS.

The following analyses provides a brief characterization of these accidents (using weighted figures).

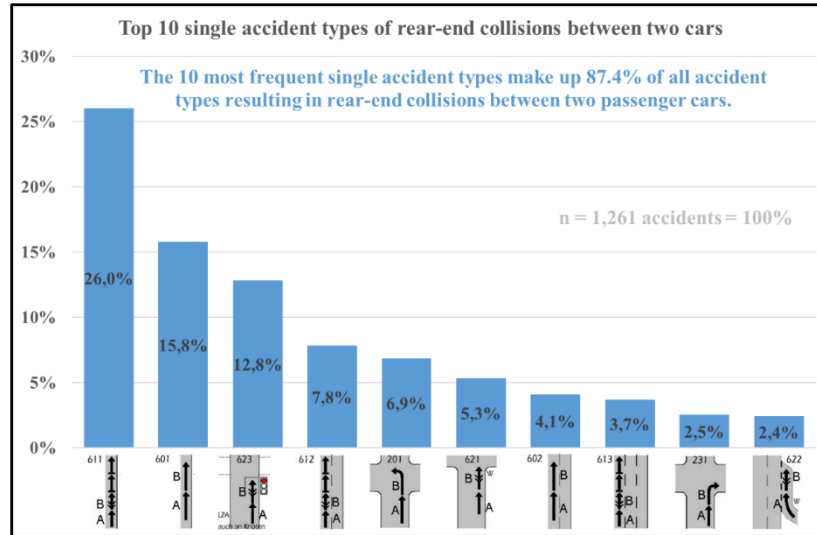


Figure 6. Most frequent single accident types in rear-end collisions between two cars (source: GIDAS)

As expected the most frequent critical situations of the considered accidents are accidents in longitudinal traffic resp. “accidents between vehicles moving along in carriageway” (group 600-699). These represent nearly 84% of all accidents in the master dataset. The remaining accidents are dominated by “Accident caused by turning off the road” which make up another 9.5%.

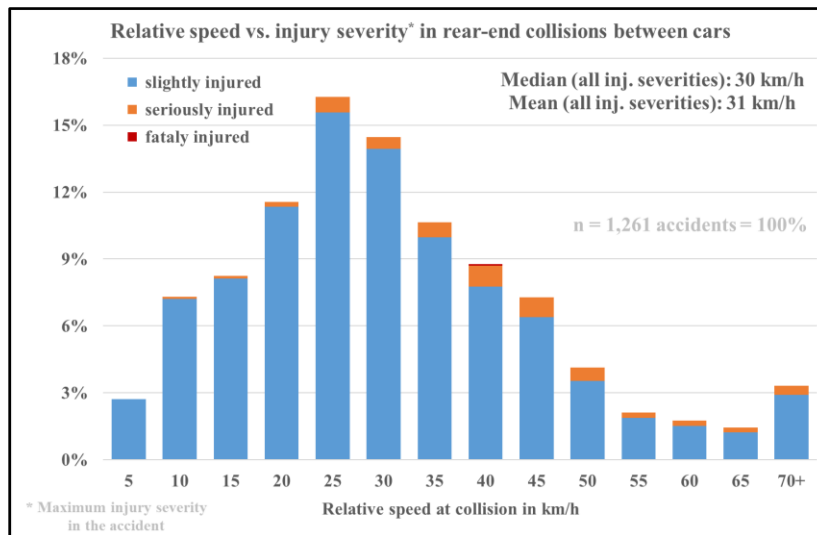


Figure 7. Relative speed vs. injury severity in rear-end collisions between cars (source: GIDAS)

Figure 7 shows the distribution of the relative speed and the documented injury severity of the accident. Here, relative speed is defined as the absolute value of the difference between the velocity vectors of the two cars at the moment of collision. It is not the relative speed at the time of the critical situation. The injury severity is the highest in-

jury severity of the accident. It has to be considered that this injury severity must not necessarily result from the occupants involved in the rear-end collision. It may also come from another collision (in multiple collision accidents) or from another road user that is involved in the accident.

On the one hand, the figures shows the speed differences that occur in rear-end collisions between two cars. However, this diagram tells nothing about the absolute speed level. A relative speed of 30 km/h can occur when a car collides with the back of a standing car or in a highway collision where a car with a speed of 160 km/h collides with a preceding car that is running at 130 km/h. The relative speed is identical but the collision energy may be different.

On the other hand, it can be seen that the vast majority (94.1%) of rear-end collisions leads to slight injuries only. There are only few accidents with serious injuries (5.8%) and only one accident (< 0.1%) at a relative speed of 42 km/h is a fatal one (a highway collision with an old car that resulted in a rollover).

Application on idealized rear-end collisions

To compare the model results with other approaches from literature, that refer to idealized constellations only, the model is applied to the idealized rear-end collision scenario first (see in Figure 8). It is important to point out that “relative speed” in the following chapters as well as in the literature source is the difference between the vehicle’s speed vectors prior to the collision (difference between initial speeds) and not (like in the paragraph above) at the moment of the collision.

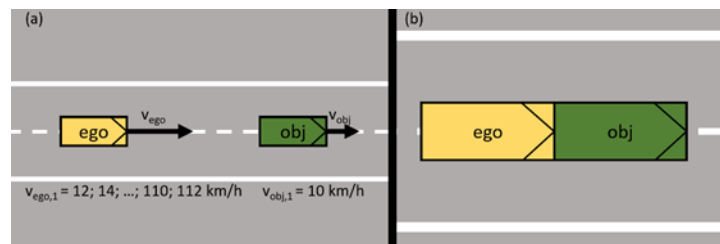


Figure 8. Scheme of the idealized rear-end collision scenario [5]

Figure 9 shows the PONR in seconds (here called t_u) as a function of relative speed between the two vehicles in km/h in the range of 0 to 100 km/h. The results visualize very well the most effective avoidance strategies and the common braking – evading boundary. Considering a decreasing friction value μ_{Road} (left graph), the gradient of the avoidance by braking function is increasing and the bound of the most effective avoidance strategy moves towards lower relative speed. Especially the comparison with Seiniger [8] ($\mu_{Road} = 1.0$) shows very close results and suggests the ability to apply the model for real accidents in a forward simulation. The offset to Reinsch [7] can be explained by differences in the model approach regarding access period of 0.3 s and swell period of 0.7 s.

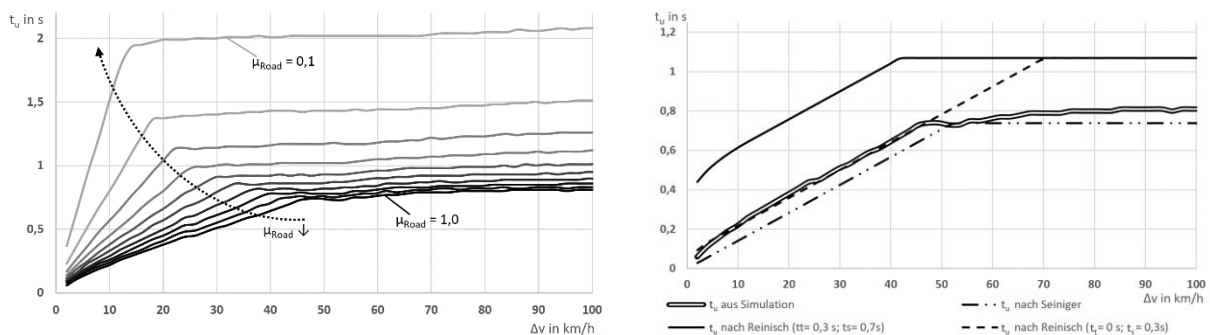


Figure 9. PONR as a function of the relative speed between the two vehicles ([5] in reference to [7] and [8])

Application on real world rear-end collisions

In the second step, the developed model is applied to the 1.019 GIDAS accidents with rear-end collisions of two vehicles as described above. The calculation precision of the PONR is $\varepsilon = 10 \text{ ms}$. Even though the described approaches for reducing simulation time are applied, the entire simulation time is around 11.5 days on one CPU and 42.000 iterations are performed (≈ 41 per case). Figure 10 shows the distribution of the calculated PONR rounded to 0.1 s. The large number of PONRs in the area of 0.6 – 0.9 seconds suggests a quite large potential for further safety systems. The low proportions below 0.3 seconds mostly represent low-speed accidents with minor consequences for the occupants. PONR above 1.6 s occur very seldom. These are mainly high speed highway collisions.

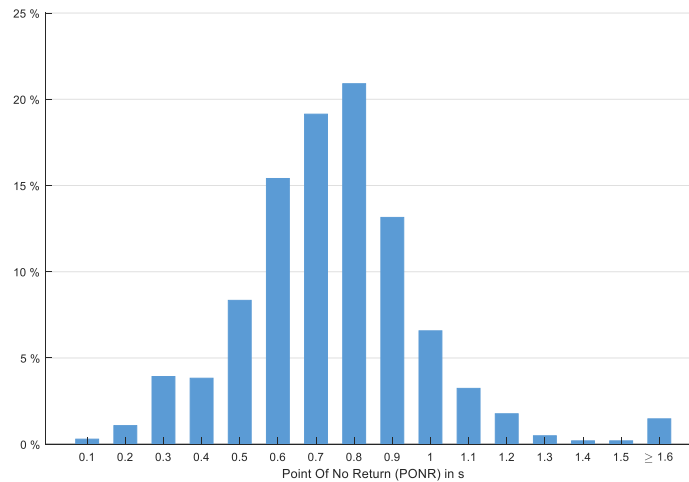


Figure 10. Relative proportions of the calculated PONR for $n = 1.019$ rear-end collisions from GIDAS

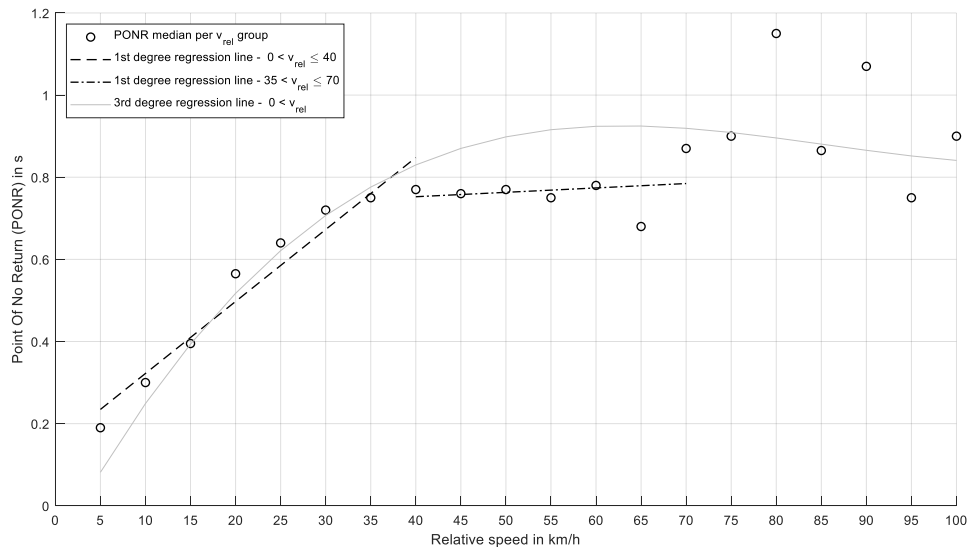


Figure 11. PONR as a function of the relative speed between the two vehicles calculated for $n = 1.019$ rear-end accidents from GIDAS

Figure 11 shows the calculated PONR as a function of the relative speed between the two vehicles, visualizing the median value per 5 km/h group. The values are unexpectedly close to the idealized scenario in the area of $0 <$

$v_{rel} \leq 60$ (compare Figure 9) as the parameter and specific attributes for real accidents spread widely. The sample contains not enough cases above 70 km/h to rely on the calculated values and the PONR is largely spreading.

The most important differences that occur in the real scenario compared to the idealized scenario are:

- Offset of the two vehicles (usually within one lane but not exactly overlapping x-axes)
- Collision angle within $\pm 15^\circ$
- Driving through curves
- Varying μ_{Road} (source reconstruction)
- Approach limit for the steering model at high speed (skidding)

The 1st degree regression lines in the area of $0 < v_{rel} \leq 40$ and $35 < v_{rel} \leq 70$ represent the two avoiding strategies braking and evading respectively, for the majority of the cases. Especially the gradient of the first regression line is in the area of the theoretical approaches even though the μ_{Road} values are highly diverse. The 3rd degree regression line for the entire area must not be over-interpreted and is therefore grayed out. It shows the general behavior only.

LIMITATIONS AND DISCUSSION

The calculated values are based on a theoretical model including limitations as well as neglecting some effects. Even though the model shows significant results, model limits as well as uncertainties must be considered for all interpretations.

Uncertainties of in-depth accident data and reconstruction

In-depth accident investigation and reconstruction as described above is always accompanied by uncertainties [18]. This cannot be avoided, as the event has already been gone when it is considered. The investigation collects as much evidences as available a posteriori and the reconstruction tries to determine the sequence of events leading to the accident and its consequences. Therefore velocities, the coefficient of friction, and other reconstruction parameter must be considered with a certain confidence interval. In addition, the exact driver reactions are estimated based on the drivers statements in combination with the accidents result and all other contributing information. Due to the physical constraints that lead to the limits of vehicle dynamics, the suggested approach is especially sensitive to the coefficient of friction.

Underestimation of the PONR due to model boundaries

The suggested approach describes some model simplifications. Some have been introduced by purpose to avoid an unreasonable extent at this state of the approach, but can be improved in future. It is important to state that probably no regular driver and no real vehicle does reach the model values for acceleration, deceleration, or steering velocities. This is especially true for the reaction period and vehicle access period.

The following model limitations introduce a systematic overestimation of the vehicle's possibilities and therefore an underestimation of the PONR values. This suggests that the actual potential for vehicle safety systems could be even higher than shown in the results.

- Clothoid evasion with constant steering velocity instead of a lane change (e.g. 5th / 7th degree polynom)
- No / low consideration of collisions with the environment or leaving the road
- No consideration of traffic flow

In contrast the assumption that Car2Car or Car2X-communication is completely or partially possible with ideal or noisy signal, leads to the possibility of cooperative avoidance strategies (meaning 8 maneuvers for both vehicles leading to 81 combinations). Under consideration of this subject the current independent approach overestimates the PONR.

Finally, there is the definition on a fixed partition of the maximum transferable force for longitudinal and lateral combined maneuvers (e.g. steering + braking, see Figure 2). Other partitions could lead to a shift of the PONR, but their influence in magnitude as well as direction cannot be predicted at the moment.

Application on other data or other purposes

The suggested approach can estimate the PONR for real accidents. An adaption towards naturalistic driving data as well as real time estimation is conceivable. This would signify a crucial contribution to the current research on the distinction between accidents and incidents. However, some adaptations would be necessary to enable such calculations.

Furthermore, it can be used to evaluate collision avoidance strategies and to parameterize some Advanced Driver Assistance Systems (ADAS). It can also contribute to the estimation of a traffic scenario's criticality as a surrogate safety measure. However, friction coefficient values are currently unknown for safety systems and cannot be used for the model parametrization.

CONCLUSIONS

The PONR is an important value to improve vehicle safety as it is the final point where all available safety measures must be activated to avoid personal damage. As this point is not measurable in reality and current analytical approaches are not sufficient to apply on real accidents, this paper introduces an advanced approach using numerical simulation. The developed approach estimates the further potential of passive and integral safety systems regarding earlier activation times. Furthermore, it can be used to evaluate collision avoidance strategies like steering versus braking as well as for parameterization of Advanced Driver Assistance Systems (ADAS).

The calculated PONR as a function of relative speed for a sample of 1.019 rear-end collisions between two cars show significant results compared to the existing analytical approaches in literature. This verifies the applicability of the approach towards traffic accidents at least for the rear-end collision scenario. Further accident scenarios can be treated by the same approach in future. The distribution of all PONR shows that passive safety measures could be possibly activated 0.3 – 1.1 seconds prior to the imminent collision for the majority of the cases. Therefore, occupant protection can be further improved by enabling already existing but unused potentials, and accidents consequences could be mitigated even more.

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