

SIMULATION OF TEST DRIVES BY USING POLICE-RECORDED ACCIDENT DATA AND COMBINING MACROSCOPIC AND MICROSCOPIC ELEMENTS

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ABSTRACT

With the development of autonomous driving functions, the evaluation of their functional safety is becoming increasingly important. Current vehicles are tested with separate simulations or test drives. In order to validate future autonomous vehicles by means of test drives, a substantial number of test kilometers are necessary. In addition, these test drives must be repeated for every new release of the system, which increases the expenses for validation. For this reason, programs that can simulate test drives have a high significance. Previous programs do not include the indispensable combination of routing simulation and accident simulation needed to represent a simulated test drive. Therefore, an approach to combining a macroscopic simulation (routing simulation) with a microscopic simulation (accident simulation) is used in this paper.

When the start location and the destination are given, the macroscopic simulation can compute the test route by means of the OSRM (Open Source Routing Machine) routing application. While driving along the test route, the simulated vehicles pass various locations of real accidents. The relevant data is taken from the accident database compiled by the police of Saxony, Germany.

A selection procedure ensures that only relevant accident situations along the test route are later simulated microscopically. Only if the accident situation is similar to the current situation of the simulated vehicle can the accident situation be simulated microscopically. Therefore, various boundary conditions are used to determine whether there are similarities regarding weather, traffic, light conditions and trajectories of the accident vehicles. To study different variations of the selection procedure, three different concepts are developed and evaluated. The first concept is based on a given test route between start location and destination and a realistic calculation of the travel time. The second concept is also based on a given test route but combines this with a time window for the entire route. The third concept combines an unknown test route, which is calculated between relevant accident locations during the simulation, with a realistic calculation of the travel time. After the evaluation of all three concepts, only the third concept is implemented in the simulation.

Within the microscopic simulation by means of PC-Crash, a relevant accident situation is simulated twice, once without and once with the tested driver assistance system in action. With the help of a collision detection system, a conclusion about the efficiency of the driver assistance system is made. The result is a program that combines completed test kilometers with avoided accident situations to simulate a test drive.

The current program can only be used in Saxony, Germany. For an expansion to all of Europe, comprehensive accident data is necessary. In addition, the selection procedure could be improved by means of georeferenced weather and traffic data. Because of the basic simulation tools, the actual simulation is not designed for quality but rather for quantity. However, high-quality simulation tools can be implemented with little effort. The simulation of test drives is an important challenge, and with the program developed here, an opportunity to solve it is introduced.

OBJECTIVE

In the development process of automated driving functions, the evaluation of their efficiency is unavoidable. Currently, simulations as well as test drives are used for evaluation purposes. With the help of repeated simulations of real accidents, it is possible to estimate whether an accident could have been prevented if the vehicle had been equipped with an Advanced Driver Assistance System (ADAS). Test drives in road traffic or on test tracks, on the other hand, expose the ADAS in question with real or staged situations [1].

In the future, the homologation process for highly automated driving functions and autonomous vehicles will become increasingly important. Currently, the functionality of prototypes is established in long test drives. However, several million test kilometers must be driven in order to obtain proof of safety. This procedure must be repeated after each system modification. This means that the expenses for obtaining proof of safety will increase significantly in the years to come [2].

For this reason, the development of a way to simulate test drives is desirable. In order to state the number of test kilometers driven, it is necessary to specify the route of the simulated vehicle. A suitable simulation solution – from now on called macrosimulation – is used for this purpose. Furthermore, an appropriate selection process for specific accident scenarios is developed within the scope of the macrosimulation. These scenarios are then studied microscopically. This way, it is possible to make a claim about how many of the selected specific accident scenarios could have been prevented by the system under testing. This is achieved with the help of a simulation that maps the interaction of the party who caused the accident and other parties involved in the accident. This simulation will be called microsimulation from now on.

METHODS AND DATA SOURCES

The combination of macroscopic and microscopic simulation elements allows the simulation of a test drive. Using the OSRM navigation application as a macrosimulation tool, the test route can be calculated from given points of origin and destination, and the vehicle's position can be simulated depending on the time. The following elaborations are visualized by the schematic depicted in Figure 1.

During the test drive, the simulated vehicle will be faced with several accident scenarios. The database of police-recorded accident data in Saxony provides the basis for all possible specific scenarios. An integrated, three-level selection process ensures that not only accident scenarios relevant in terms of time and location are considered for microsimulation, but also those that show similarities to the simulated vehicle in terms of traffic situation, weather and lighting conditions, as well as trajectories of the involved parties. The similarities are determined and guaranteed by applying several framework conditions. One example of a framework condition is the limitation of the time of the specific accident scenario to the arrival of the simulated vehicle at the accident location. The smaller the time difference to the specific accident, the greater the similarity of the oscillating traffic volume and the lighting is believed to be.

Three different concepts for the integration of the macrosimulation and the corresponding selection process will be developed and compared.

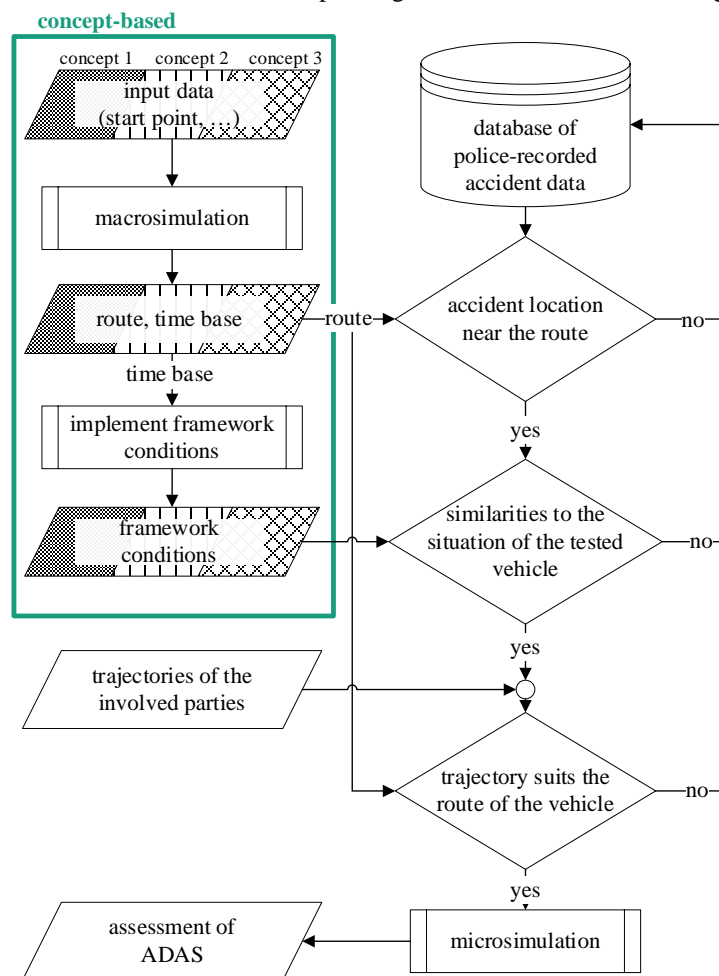


Figure 1: schematic of the selection process

The third and last step of the selection process is based on the intended trajectories of the involved parties. These, as well as the real trajectories, are generated at the Fraunhofer IVI on the basis of the accident data. In order for a certain accident scenario to be selected, one of the intended trajectories needs to correspond with the simulated course of the test vehicle. It is only possible under these circumstances that a vehicle at the same precise location and under similar framework conditions will be involved in an accident similar to the existing concrete accident scenario. If, for example, the simulated vehicle makes a right turn at an intersection where a left-turn accident has occurred, this accident simulation cannot be submitted to the microsimulation.

Within the microsimulation, a statement is made about whether there is a collision between the parties involved. By executing separate simulations with and without a system under testing, it is possible to assess whether the system is able to prevent an accident. In combination with the length of the test route, a claim can be made about test kilometers driven, simulated accidents as well as prevented accidents.

Development of three concepts for the integration of the macrosimulation

Each of the three concepts is based on the macroscopic calculation of a test route between points of origin and destination. The concepts differ in the integration of the macrosimulation and the establishment of framework conditions for the selection process.

Concept 1 adapts a real test drive. The route is known prior to the start of the simulation, meaning that the points of origin and destination are also known. A route is generated between these two points under consideration of any desired number of intermediate points.

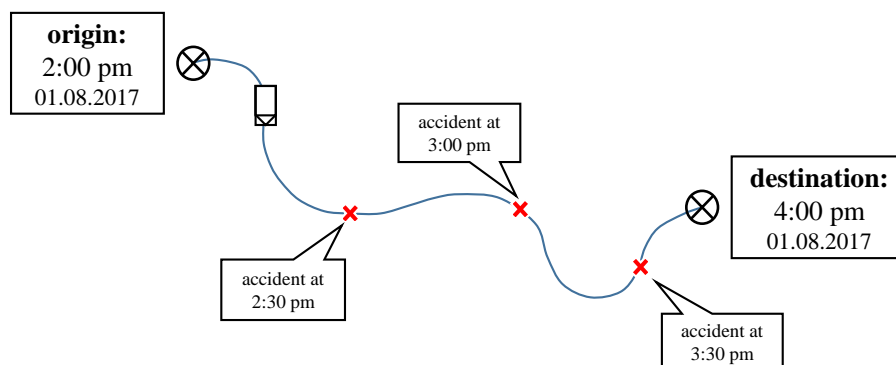


Figure 2: schematic of the first concept

Figure 2 shows the schematic structure of the first concept. The blue line depicts the route from point of origin to point of destination. In concept 1, all accidents along this route with a maximum distance of 15 m to the middle of the road are extracted from the database. The red crosses depict these accident locations along the route. Concept 1 also requires a start date and time, henceforth called the start time stamp. With the help of the start time stamp, it is possible to calculate the position of the test vehicle along the route. The result of this calculation is one arrival time stamp for the point of destination and arrival time stamps for each of the accidents extracted. In addition, each accident also has an accident time stamp describing the date and time at which the accident occurred. The accident time stamp can be extracted from the database of police-recorded accident data. If a simulated vehicle reaches the accident location close to the accident time stamp, the vehicle's situation is similar to the situation. If a simulated vehicle reaches the accident location close to the time of the accident time stamp, its situation is similar to the situation causing the accident. A higher proximity between arrival time stamp and accident time stamp means a higher similarity.

Concept 2 is based on concept 1. Just as in concept 1, a route is generated between the points of origin and destination. This route is shown as blue line in Figure 3.

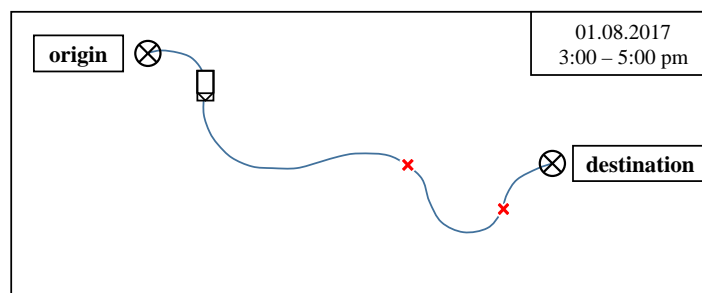


Figure 3: schematic of the second concept

Then, all accidents along the route that are close to the road are looked up. Similar to concept 1, each accident has a time stamp. However, concept 2 does not calculate when a simulated vehicle reaches the accident location. Instead, accidents are selected on the basis of a freely configurable time window. For the example shown in Figure 3, this means that every accident between 3:00 pm and 5:00 pm is selected (red crosses). It is irrelevant in this case whether the simulated vehicle would be able to reach the accident locations in the given time or whether the accidents are depicted in a chronological order. The result of this abstraction is the simulation's loss of direct comparability with real test drives.

Concept 3 is comparable to a real test drive because the calculation of its duration is realistic. However, the drivers do not know their final destination at the start of the test drive. Instead, they receive a new destination after they have reached a given intermediate destination. At the start of the simulation, only the point of origin, the start time stamp and the minimum distance of the test route are known.

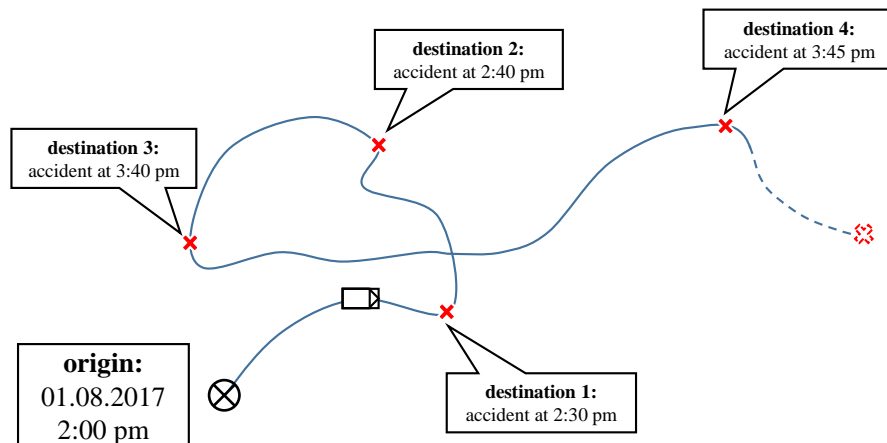


Figure 4: schematic of the third concept

Figure 4 shows the schematic structure of the third concept. The point of origin and the start time stamp are visualized by a black circle with a cross. A pre-defined route, however, needs a destination. To determine a destination, all relevant records are filtered out of the database of police-recorded accidents in Saxony. Then, the distances between the point of origin and all extracted accident location is calculated. The accident location closest to the point of origin becomes the destination of the first route segment (red cross in Figure 4).

An arrival time stamp is calculated for the selected accident location. Based on the arrival time stamp there is an assessment of whether the lighting conditions at the time of arrival are similar and whether the difference between the time of arrival and the time of accident is tolerable. If, considering all framework conditions, the accident scenario is still valid at the simulated vehicle's arrival at the accident location, the scenario can be submitted to the selection process and simulated microscopically.

After this, a destination for the following route segment is determined. The new point of origin is the location of the current accident scenario and the arrival time at the accident location becomes the new start time. As described above, all relevant records are extracted from the database and the distances to potential points of destination is calculated. Again, the closest accident is defined as destination of the current route segment. This loop is continued until the test vehicle has exceeded a predefined number of test kilometers. At this point, the simulation according to the third concept is terminated.

Evaluation of the three concepts

Before the three concepts can be compared to each other, each concept needs to be defined rigidly. For this, each concept is assessed in terms of its possible framework conditions for the selection process so that in the end, each concept is defined by a special combination of rigidly implemented framework conditions. The following three criteria are considered in the specification of the framework conditions.

The first criterion is the number of selected accidents per 1,000 km distance. To determine this figure, the absolute number of selected accidents is divided by the test kilometers driven. According to the statistics on road traffic accidents in the year 2016 compiled by the German Federal Statistical Office (Statistisches Bundesamt, Destatis) [3], about 3,375 accidents per 1 billion kilometers driven occurred in 2016. Or, to put it differently: On average, there was one accident every 296,296 kilometers. This corresponds to 0.003375 accidents per 1,000 km. However, it is not practical to use this figure as an evaluation standard for the first criterion. In order to test a system, a much higher number of accidents per kilometer should be simulated. In order to achieve a compromise between higher accident numbers and the highest possible comparability of vehicle and accident situations, a range of 50 to 100 accidents per 1,000 km is desirable.

The second criterion is the representativeness of the selected accidents within the context of all available police-recorded accident data. The database of accident data recorded by the Saxon police includes, among others, all police-recorded accidents between 2010 and 2016. Each of these accidents is described by characteristic features such as accident category, kind of accident, type of accident and area (urban, rural). This means that the distribution of these features within the Saxon database reflect the general accident situation in Saxony in the past years. It is therefore desirable to achieve an approximation of this distribution within the planned simulated test drive.

The third criterion is the logical comparability of vehicle situation and accident scenario. The repeated simulation of a past accident becomes more comprehensible if the situation of the simulated vehicle and the situation that caused the accident are as similar as possible. Different framework conditions may decrease or increase the similarities between the two situations. Therefore, the framework conditions must be studied in terms of their effects.

After the analysis and subsequent definition of the concepts framework conditions, they can be compared. This process takes into account seven criteria that are weighted differently. After the evaluation of all concepts, it is possible to identify the best one.

Trajectory-based analysis of selected accident scenarios

The selection process for the microsimulation is carried out partly based on concepts (within the concepts) and partly independent from concepts (outside of the concepts). Trajectory-based selection is the part of the selection process that is independent from concepts.

Upon the arrival at a selected accident location, the simulation program examines whether the course of the simulated test vehicle corresponds with the intended course of a party involved in an accident. If the courses correspond, the test vehicle is allowed to simulate the specific accident scenario in the role of this specific party only. Figure 5 shows the schematic of a potential accident scenarios along the test route. The party causing the accident (red) collides with the injured party (blue) while making a left turn. The course of the simulated test vehicle (green), however, does not correspond with either of the two intended courses. In this case, the specific accident scenario was selected within the concept on the basis of framework conditions, but it may not be used within the microsimulation because the course and the trajectories do not correspond. This is the reason why it is important to establish a method for assessing the courses and trajectories of the parties involved in an accident.

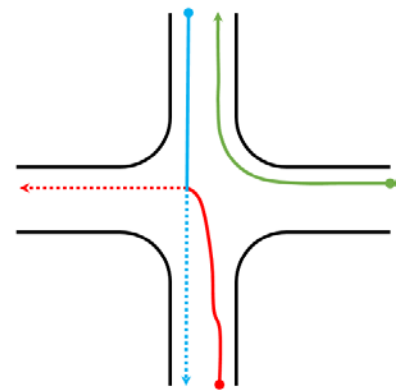


Figure 5: Necessity of the trajectory-based selection

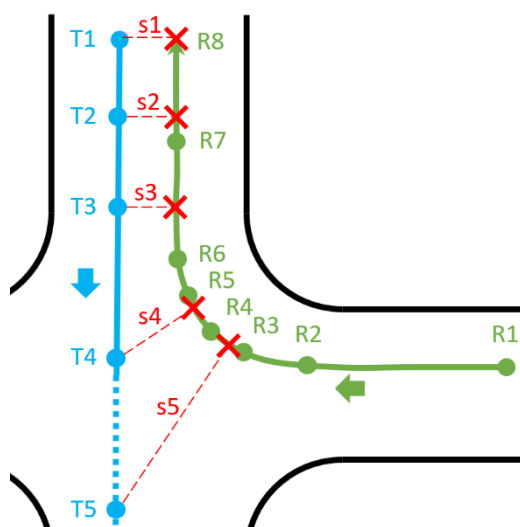


Figure 6: sketch of the solution approach of the trajectory-based selection

The solution of this problem is a method that combines the evaluation of the distance between course and trajectory with the evaluation of the direction of travel. The course and the trajectories are defined by any given number of points represented by geographic coordinates (from now on called supporting points). In Figure 6, these are visualized by the round dots. For each supporting point of the trajectory (blue), the shortest perpendicular distance to the course (green) is calculated (see s_1 to s_5). The resulting vector of shortest distances \bar{s} can be studied in terms of various parameters such as mean value and standard deviation.

In order to compare the directions of travel, it is necessary to analyze the order of the trajectories supporting points (T1 to T5) and their corresponding closest course supporting points (R1 to R8). For this, each trajectory supporting point T_x is matched with the route supporting point R_x that is closest to the point depicted by the red cross in Figure 6. For example, T1 is matched with R8, T2 is matched with R7 and T3 is matched with R6. This way, two vectors are formed that contain the figures of the matching points (for example: $\bar{T} = [1; 2; 3; 4; 5]$ and $\bar{R} = [8; 7; 6; 5; 3]$).

After that, it is possible to estimate the strength of the linear relation of the two vectors \bar{T} and \bar{R} by using the Pearson correlation ρ according to the Equation 1.

$$\rho = \frac{cov(\bar{T}, \bar{R})}{\sigma_{\bar{T}} * \sigma_{\bar{R}}}, \text{ with } cov() - \text{covariance und } \sigma - \text{standard deviation} \quad (\text{Equation 1})$$

In order to test which parameters (mean value, standard deviation, ... , ρ) allow the identification of suitable trajectories, a test data set is compiled. The basis of this are 18 different random accidents with known trajectories. For each of the accident locations, all courses in all possible directions are established. Then, a manual assessment is carried out for each of the 256 route-trajectory-pairs of whether they are approximately parallel. If this is the case, a distinction is made between “right direction” and “wrong direction”. With the help of several graphic representation methods, it is then possible to determine which parameters allow the identification and selection of suitable trajectories (along the course, right direction).

Microsimulation

The selected accidents are automatically transferred to the microsimulation via an interface and then analyzed. Because the PC-Crash software can easily be integrated by external applications and also supports trajectory-based collision detection, it is used as microsimulation software.

Input data such as the real trajectories of the parties involved in the accident, their speeds and initial locations provide the basis for microsimulation. The maximum allowed speeds of the involved parties can be found in the police-recorded accident data, an uniform movement is assumed. The initial locations of both parties are deduced on the following assumption: the vehicles of both parties collide at the end points of their real trajectories. Based on this assumption, possible initial locations for each party can be established with the help of a reverse simulation along their trajectories that starts at the end points.

The result of the microsimulation consists of two return values. The first return value stores the information whether a collision has occurred without the system under testing, thus error-proofing the process. The second return value gives information about whether the vehicles collide while the system under testing is active. If the first return value is negative (no collision), then no claims can be made about the effect of the system under testing on the basis of this specific accident scenario. If the first return value is positive, a second step describes whether a collision was prevented by the system or not. The system’s effects can then be evaluated based on the accidents prevented.

RESULTS

The results of the comparison of the three concepts are depicted in Table 1.

*Table 1.
Comparison of the three concepts with the help of a weighted decision matrix*

Criterion	Weighting	Concept 1	Concept 2	Concept 3
Comparable with reality	5	9	4	9
Accident numbers along the test route	2	5	5	9
Options of test route manipulation	3	2	2	8
Functionality of long test routes	5	3	2	10
Options of influencing the testing environment	2	5	9	0
Functionality in case of missing accident data	4	10	10	9
Option of expanding the simulation to further regions	5	9	9	7
Result [Percentage of maximum points attainable]		66 %	57 %	80 %

Table 1 shows that each of the concepts has its advantages and disadvantages. However, for the simulation of a test drive under the given requirements, the third concept is the most suitable one.

Results of the trajectory-based selection process

The analysis of the parameters for the identification of suitable route-trajectory pairs had the result that no single parameter offers a finite solution. Instead, a combination of the standard deviation and the Pearson correlation coefficient is used. Figure 7 shows which threshold values need to be defined.

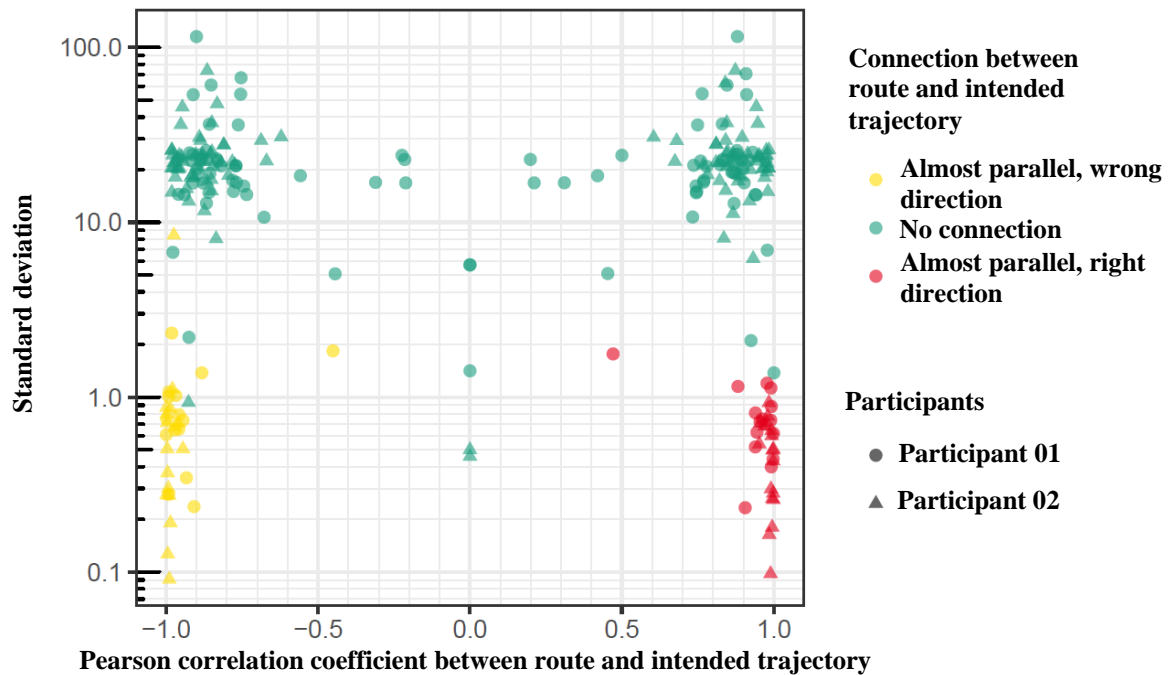


Figure 7: standard deviation and correlation coefficient (256 route-trajectory pairs)

Based on the above image, the trajectory-based scenario selection procedure is implemented as follows: For the examination, the type of road use of the trajectories taken into account is limited to the class of “passenger car”. For example, pedestrian trajectories are not allowed. The remaining intended trajectories can be examined with the help of the standard deviation and the correlation coefficient. In 97% of cases, trajectories with a standard deviation $\sigma \leq 3$ and a correlation coefficient $\rho \geq 0,8$ are suitable for the current route and go in the right direction.

Example application of the program

The example application demonstrates the entire process of the developed program using a vehicle equipped with an advanced emergency braking system (AEBS). At the beginning of the example application, the input data is defined. The test drive begins on August 1, 2017 at the Fraunhofer IVI in Dresden and covers a distance of 100 km or more. The system under testing is mapped in PC-Crash with the help of a proximity sensor with a range of 80 m, an opening angle of 5 degrees and a cycle time of 100 ms, as well as with an active TTC time to collision monitoring system. If the TTC falls below 1 second, an emergency braking process is initiated.

Within 11 minutes, the program carries out the construction of the route, the selection process and the microsimulation. The resulting test route of 109 km length is visualized in Figure 8 by a transparent green line. It passes through Dresden’s urban center as well as through surrounding areas. Along this route, the test vehicle is confronted with 18 selected accident scenarios. 14 of these pass the trajectory-based selection process and are then simulated microscopically. The results are summarized in Figure 9.

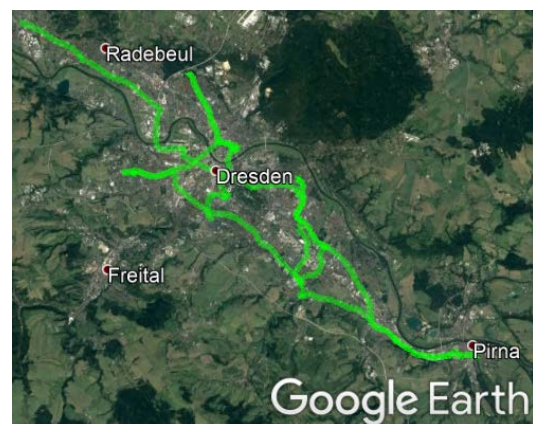


Figure 8: test route of the example application

The 14 simulated accident situations are plotted according to their types of accident and distinguished by color. Only those accident situations that were prevented by the AEBS are marked green. Thus, the efficacy of the AEBS becomes evident with respect to the different types of accident.

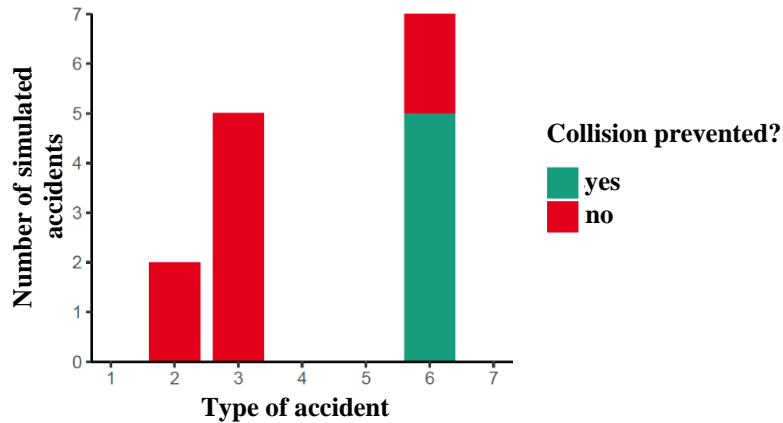


Figure 9: results of the example application, broken down by type of accident

According to Figure 9, the AEBS is able to prevent over 70 % of accidents in parallel traffic (accident type 6) within the simulation. However, no accidents are prevented during turning and during turning/crossing accidents (types of accident 2 and 3). This leads to the conclusion that the AEBS in use is mainly effective in rear-end collisions. Further examination of the simulation files created by the microsimulation confirms this conclusion. Only in the situation of a rear-end collision on a straight road is the injured party detected in time, so that an emergency braking process can prevent the collision. In rear-end collisions in turns and in all other accident situations included in the simulation, the injured party is not detected or not detected early enough.

DISCUSSION

The integration of traffic and weather data would be very beneficial for the area of the macrosimulation. The implementation of other external macrosimulation applications is also conceivable to and the modular design of the program supports this.

The selected variant of microsimulation is able to draw a conclusion about prevented collisions. However, a more detailed realization of sensors and advanced driver assistance system would improve the plausibility of results. Also, no exact input parameter exist for the microsimulation, which is why they need to be deduced with the help of assumptions. Thus, there is a potential for an expansion of the microsimulation. Due to the modular design of the program, the microsimulation could also be realized through the implementation of other simulation programs.

In order to evaluate the simulation of an entire route, the accident selection is studied in terms of representativeness by comparing it to a reference data set. For this, the distribution of the double-digit types of accident of the selected accidents is examined in the context of the distribution of the double-digit accident types of the reference data set. The result of the comparison provides the basis for a two-level score, which is calculated automatically. This score first examines how many of the types of accident are reflected in the accident selection. Subsequently, it evaluates how well the reflected types of accident are represented. The score has values between 0 and 1, where 1 symbolizes a perfect reflection of the overall data set.

The score of the example application was calculated to be 0.38, which means an inadequate representativeness. Although 5 of 14 collisions were prevented, the statement “The AEBS is able to prevent 5 in 14 (35%) accidents” is a misinterpretation. A longer test route with an increased number of simulated accidents would improve chances of a higher score and a more well-founded statement.

CONCLUSION

Due to the necessity mapping test drives in a simulation environment, a method was developed that allows a statement about test kilometers driven and accidents prevented. To achieve this, a simple macroscopic simulation of a test vehicle was combined with a selection process for specific accident scenarios with the objective of transferring selected scenarios from the macroscopic simulation to the microscopic simulation. On the basis of multiple simulation, the latter allows to draw a conclusion about the collision prevention potential of the system tested.

The reduction of effort and expenses for real test drives will be possible with the help of the described method. If comprehensive accident data is available, the expansion of the simulation to additional regions will be possible.

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