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Modelling Driver's Behaviour While Avoiding Obstacles

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Abstract: This article presents a short description of mathematical driver models. In the literature, there are no models that are generally considered fully satisfactory for use in analysing drivers' behaviour in emergencies. This paper presents a concept of model, which includes two sub-models related to the driver's defensive manoeuvres—avoiding the obstacle and braking. This article describes a model used for a simple road situation—a single obstacle (pedestrian) appearing on the road in front of the vehicle. In the model, the method of artificial potential fields was used, but it was enriched with the concept of safety zones around the vehicle and obstacles for three variants of the proposed shape, namely a rectangle, a circle, and an ellipse. In the simulations, parameters important for the model's operation were used. The proposed model can be used for the simulation of human behaviour in specialised programs for accident reconstruction and in the future in assistant systems.

Keywords: accident situations; driver behaviour; driver model; avoiding the obstacle; steering wheel angle

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1. Introduction

Modelling the behaviour of drivers is not a recent issue. For many decades, research has been carried out to mathematically describe the activities of a driver in various road situations. It is a complicated goal because the driver's behaviour is a very complex issue. Even how the same driver reacts to a threat in various road situations may be different. Various factors that appear in a given place and time may significantly determine the driver's behaviour.

The psychological characteristics of a driver that influence his or her driving behaviour include, for example, the ability to anticipate the situation, driving experience, underestimation of possible dangers, or a tendency to take risks. Last but not least, factors resulting from the driver's long working time, sleepiness, mental fatigue, and nervousness, as well as previous neurological diseases, are important in this respect. The influence of these factors on humans is still being analysed by many researchers, which has been confirmed by a very large number of publications in this field [1–5]. Taking into account the driver as a human, no less important factors influencing the way he/she reacts to various road situations are his/her physiological features. Manual skills, motor limitations (important especially in older people or those after orthopaedic surgeries), sight and hearing, complex dysfunctions caused by past diseases, and physical fatigue may significantly affect the way a driver behaves. How the driver perceives threat can depend on various factors. The lighting of the road, the current time of day, sleepiness, and driver working time significantly affect steering [6] or exploitation conditions [7]. The division of drivers' "abilities" based on gender or age alone, taking into account the variety of factors mentioned, is, therefore, insufficient [8–12]. In this paper [13], the results of tests carried out in a driving simulator are discussed. The main objective of this test is to determine the effects of the distraction of drivers on driving performance.

The drivers were subjected to various distracting activities. They had to use a multimedia system in the vehicle or talk to a mobile phone using the hand-free system. Tests were carried out in road environments for various hazard situations, e.g., pedestrians standing on the road, crossing the road, and cars reversing down the driveway. The analysis confirmed that distraction worsens driving performance and the way drivers respond to threats. At the same time, a distraction increases the subjective feeling of the driver's workload. One of the main key differences detected in driver behaviour was that older drivers travelled at a lower average speed in a complex motorway environment compared to younger drivers.

Publication [14] describes the identification of many parameters related to vehicle control, which were used to identify various types of driver behaviour. In the publication [15], measured driving speed, maximum speed values obtained, and longitudinal and lateral acceleration were used to determine the drivers' styles. Lateral acceleration is often used to determine the driver profile and it is one of the best parameters for the analysis of avoiding-the-obstacle manoeuvres [16–19]. Driver models are designed to be a simplification of a "real driver", with the complexity of the model depending on its intended use. Simpler models are relatively easy to use, but their use can only be limited to certain applications. More sophisticated models, although covering a wider range of applications, are more difficult to use in simulations due to the much higher number of parameters needed to identify them. Given the above, the development of a relatively complete yet versatile driver model is still an unaccomplished goal. Therefore, simpler models are being developed more frequently, targeting narrower specific applications. One possible application of driver models is to reproduce the behaviour of the "average driver" in pre-crash situations. Such models are used, inter alia, in the development of driver assistance systems, autonomous vehicles [20,21], or accident reconstruction programs [22–25]. These programs very often do not take into account the impact of the driver during the road accident and the defensive reactions undertaken by the driver at that time.

In the paper [26], the authors described a model of driver behaviour using the information obtained from the vehicle motion sensors. In the study [27], the authors proposed a method for the real-time identification of a driver model. This method requires the calculation of simple motion parameters: yaw rate, steering angle, and velocity. In the paper [28], the analysis of the driver behaviour in semi-autonomous driving was described. The authors determined how the message accompanying the car's autonomous driving affects the driver's behaviour.

Various driver models are used to analyse the driver–vehicle–road (surroundings) relationship. These models describe typical driver behaviour without taking into account the abundance of possible driver reactions in different road situations. It is very difficult to build a complete driver model that takes into account most of the driver's psychophysical characteristics, even with the use of computerised calculation techniques. The cooperation of specialists from various fields of science, such as medicine, psychology, and technology, still does not entail the creation of a full description of driver's behaviour. Yet, such a model should cover the full spectrum of the driver's actions. In modelling the driver's behaviour, the aim is to ensure that the results of the analyses and modelling accurately reflect the drivers' reactions and are consistent with the real world. Driver behaviour research is often based on the observation of the way drivers act in road traffic, during research conducted according to certain formulated tests in staged situations on separate test sections or special simulators.

This paper analyses many of the driver models related to the driver's actions in critical situations. The first created driver models are currently referred to as compensatory models [29]. Their operation was based on the driver's ongoing compensation for the vehicle position error concerning the assumed traffic path. However, due to their simplicity, such models could not be used to simulate many manoeuvres. They were not intended to take into account the fact that a driver, when observing the road ahead of the vehicle, tries to define a strategy for further action. In the anticipation models [30–33], the driver acted by compensating for the position error based on the expected position of the vehicle at a certain distance from it. Despite this action from the driver, the simulated motion path of a car could still be different from the real one. Therefore, further predictive models were developed [34], in which a driver was able to anticipate the future position of the car at a certain anticipation distance [35–39]. In other models, both anticipatory and compensatory activities were taken into account. An example of such a model can be, e.g., the Dong model [40,41].

In his work [42,43], Yoshimoto assumed a simple process of processing the image seen by a driver, the so-called optical flow, as the basis for driving a car. In this process, the driver reacted to a change in the position of two borderlines (two road edges or lines limiting a given lane). Many models, based on visible information reaching the driver, were created [44]. The proposed model also uses such information, and many methods of determining the position of other objects can be used, e.g., radars, ultrasonic sensors, or laser sensors. In the study described in the paper [45], the authors proposed a speed model of the vehicle motion on the curve. That model uses driving styles and other factors related to vehicle and road. The authors proposed a model that reflects, e.g., the speed preferences determined for three different types of drivers. This curve speed model could be applied in a curve speed warning system.

A similar subject concerning driver modelling was described in the paper [46]. In this paper, the authors calculated a driver behaviour factor, defined for different driving styles as the ratio of drivers' actual selected speed to the theoretical curve speed. In the paper [47], a model for predictions of driver behaviour for a turning manoeuvre was presented. The authors described that the motion parameters from a human-driven vehicle could be used to predict the human driver's decision to stop before executing a left turn.

A very important group of driver models are models that reproduce the driver's behaviour in near-accident situations. Such a model should usually take into account the defensive manoeuvres undertaken by the driver, namely steering and braking. Models, among which it is possible to search for such solutions, may also include:

- Speed control models [48,49] designed for driving control systems in the ICC (intelligent cruise control) column [50–52], in autonomous vehicles [53,54], or Internet of Vehicles [55,56];
- Longitudinal [57,58] and lateral [59] motion control models [60];
- Models for traffic flow simulation, used, e.g., to analyse the fluidity of traffic on motorways and road networks, including the assessment of the probability of pile-ups, etc.;
- Models for software used in accident reconstruction, to reproduce the behaviour of drivers in emergencies.

The traffic stream model presented in the paper [50] contains a description of a car following its predecessor (car-following model). The assumptions used to create this model can be considered typical for this group of models. The driver can use one of four modes of driving: free driving, approach, stabilisation of driving in a column, and braking. In another paper [61], a model which characterises macroscopic traffic was described. This model is based on analogies with the ideal gas law, known in thermodynamics. A traffic constant, that uses both physiological and psychological driver factors, is proposed. Physiological driver behaviour includes observing and processing local traffic conditions. A traffic constant encompassing the perception, awareness, attitude, and reaction of a driver was described.

In critical situations, one of the basic defensive manoeuvres is braking. The construction of an emergency braking model proposed in the paper [62] was preceded by studies of the behaviour of a driver driving a vehicle at a constant speed, who, at some point, encountered an obstacle in his field of vision. This is what forced the start of the braking manoeuvre to avoid a collision. An interesting review of driver models, used in critical situations, was presented by G. Markkula and O. Benderius et al. in their work [63].

Many authors state in their works that the actions of drivers in critical situations depend on the distance from an obstacle and the speed of driving. All mathematical dependencies that make up the driver model are then the functions of these two variables.

In the previous work of the authors of this article [64], a model covering two main defensive models of the driver's actions, observations made during driving in real traffic, as well as during tests in simulated conditions on a track, were used. During the avoidance manoeuvre, as well as during braking, the drivers reacted to an obstacle penetrating the roadway area. The different behaviour patterns of the driver were described, namely speed reduction (braking) and obstacle avoidance. The main parameters determining the possibility of undertaking a given defensive manoeuvre (and its intensity) was the lateral position of the obstacle concerning the lateral position of the vehicle. The vehicle speed and distance from the obstacle were equally important. In their work, e.g., [36,65], the authors showed that it is much more advantageous to use in the driver model the distance from an obstacle, but measured in time—called *TTC* (time to collision). This value is related to both parameters mentioned above, and the driver's actions in accident hazard situations (including response times) are functions of this value (Equation (1)). *TTC* (in seconds) is the ratio of the distance from an obstacle (m) to the vehicle speed (m/s)—Figure 1 [66,67].

$$TTC = \frac{S}{V} \tag{1}$$

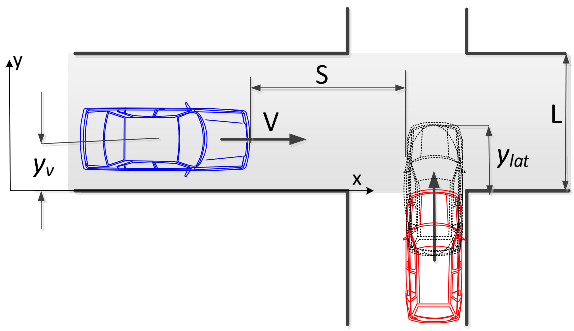

Figure 1. Scheme of a road situation.

In the authors' earlier works, this time calculation was called "Risk Time" [68].

In the driver model, a segment called "distance reserve" y_{lat}—y_v was introduced into the equations. The relationship formulated in this way caused the dependence of the amount of deceleration b of the vehicle (during braking) on the change of its lateral position in relation to the lateral position of the obstacle. The increase in the deceleration was adopted as a variable; therefore, on the left side of the equation, a derivative of the deceleration $\dot{b}$ was introduced. Finally, the braking model (Equation (2)) was supplemented with a segment related to the driver's reaction time for the braking manoeuvre *BRT* [69].

$$b(t) + W_1 \cdot \dot{b}(t) = \begin{cases} 0 \\ W_2(y_{lat}(t) - y_v(t)) + W_3\left(\frac{1}{TTC}\right) \end{cases} \text{for} \begin{cases} t < BRT \\ t \geq BRT \end{cases} \tag{2}$$

where

W_1, W_2, W_3—braking model coefficients;
BRT—braking reaction time (s);
TTC—time to collision (s);
y_{lat}—rate of penetration of an obstacle into the vehicle motion area (m);
y_v—lateral position of the centre of the vehicle mass (m);
b—deceleration (m/s^2).

The final variant of the driver model, in terms of steering manoeuvre, is described by Equation (3). The steering wheel angle δ depended on the difference between the distance of the obstacle and the change in the lateral position of the vehicle y_{lat}—y_v. The greater the angle, the "calmer" the driver's reaction. At the same time, a segment related to the derivative of the steering wheel angle $\dot{\delta}$ and to the driver's reaction time for the steering manoeuvre, *SRT* [69], was introduced in the notation.

$$\delta(t) + W_4 \cdot \dot{\delta}(t) = \begin{cases} 0 \\ W_5(y_{lat}(t) - y_s(t)) \end{cases} \text{for} \begin{cases} t < SRT \\ t \geq SRT \end{cases} \tag{3}$$

where

W_4, W_5—steering model coefficients;
SRT—steering reaction time (s);
δ—steering wheel angle (rad).

This paper presented a proposition of the driver models related to the driver's actions in critical situations. The main purpose of this model is to reproduce the driver's actions in pre-accident situations. It can be used as an additional element in programs used to reconstruct road accidents. Currently, these programs simulate the way the vehicle moves, and in most of them, the impact of the driver's behaviour is not taken into account at all. The method of describing the mutual position of obstacles and the vehicle makes it rather easy to apply the proposed algorithm to them. This does not exclude the possibility of applying this model to solutions related to assistant systems in the future, but further work is still necessary for such situations, taking into account their complexity. The model parameters used must be determined in future studies for different runs. Such studies are planned for the future.

The second chapter presents the most important assumptions of the model, while the third chapter presents the results of computer simulations of the avoiding manoeuvre for an exemplary road situation. It describes the driver's action algorithm based on the location of the vehicle and other objects (including an obstacle) around the vehicle. The model introduces a different safety zone—an area that should be intact during such situations. As mentioned earlier, the use of this model can be rather broad. It can be used in programs for reconstructing road accidents, as a component representing the driver's actions, and in the future also include solutions for assistant systems.

2. Description of the Assumption of the Driver Model

The new driver model proposed in this publication uses a modified potential field method. The use of some elements from the potential field method [70–73] used in robotics has created the possibility of a new approach for determining the algorithm of driver behaviour in road emergency situations. This method is widely used due to its ease of physical interpretation. Possible obstacles may arise in the course of traffic, and the situation changes dynamically, although in this respect the vehicle is characterised by a slightly different specificity. This is all the more important in emergencies [74–78].

A similar method, described in the paper [79], was used for the mobile robot path planning. The artificial potential field method was used to find the parameters to determine a safe path of motion. The paper [80] described a path planning method for an autonomous mobile robot, called the discrete artificial potential field (DAPF). The DAPF algorithm is capable of finding a collision-free path for a mobile robot in static and dynamic environments. The authors of the cited paper proposed the path optimisation algorithm (POA), which should modify the collision-free path to obtain a smoother and shorter path.

A driver, while driving, reacts to visible information and chooses the planned position of the vehicle, which has been defined as the target point, but also takes into account the existence of the obstacle and the edge of the roadway. A similar situation should be taken into account in the accident reconstruction process. The position of the vehicle and any obstacles in the space around the vehicle are known. The aim is to keep the vehicle in the lane for safety reasons.

When modelling the driver's behaviour in a specific traffic situation (Figure 2), the effect on point $q(x_v, y_v)$, which is the centre of the vehicle's mass, of artificial potential fields from an obstacle, from both sides of the road and the target point, was taken into account.

In this paper, an analysis of a similar obstacle avoidance process that uses one obstacle was described [81].

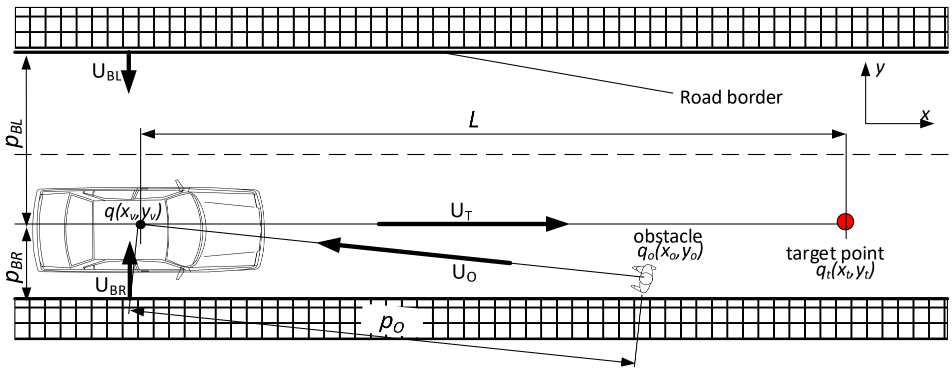

Figure 2. Scheme of interactions in the potential field.

The value of the potential field *U(q)* and affecting point $q(x_v, y_v)$ in a fixed coordinate system *(x, y)* was determined. The field consists of the interactions from the abovementioned factors: target point, obstacle, and edge of the road. The value of the potential field is expressed with the following Equation (4):

$$U(q) = U_T(q) + U_O(q) + \sum_{j=1}^{2} U_{Bj}(q) \tag{4}$$

where

$U_T(q)$—potential field to the target point;
$U_O(q)$—potential field from the obstacle;
$U_{Bj}(q)$—potential field from the left and right edge of the roadway.

In many papers describing in particular the research on the creation and verification of anticipation (prediction) models, the authors determine the location of the traffic destination point. It is "set" by the driver on the road, at a certain distance in front of the car—often called the anticipation section. In the model, we will refer to this car destination point as the target point. The potential of the field U_T being attracted to the target point can be defined as follows:

$$U_T(q) = \frac{1}{2} k_T L^2(q) \tag{5}$$

where

$L(q)$—distance to the target points;
k_T—scaling coefficient of the potential.

In developing the model concept, it was assumed that the target point is not a fixed point but is at a certain distance *L* in front of the vehicle. The concept of the observation section was used (similar to the anticipation models). The distance to the target point depends not only on the psychophysical capabilities and perception of the driver (e.g., eyesight condition) but also on the way the road is shaped. In the case of straight road sections and low traffic volumes, this distance can be assumed to be greater because the driver can "look" further ahead and "set" the assumed target point at a greater distance. It will be different when the vehicle is moving on winding, hilly roads, at high traffic density, in dynamically changing traffic situations. Then, the distance to the target point is shortened. While driving, the observation point can "change" its position as the moving vehicle changes its position. It can therefore be assumed that when driving at a constant speed along a straight road section, the distance to the target point remains constant and the influence of the attraction field is also constant. When the road situation becomes dynamic (there are some disturbances, e.g., sudden obstacles), the observation distance *L* can also be subject to dynamic changes. Important elements affecting the driver included in the model are obstacles near the vehicle. The repelling potential U_O, acting on the vehicle from an obstacle with coordinates (x_o, y_o), depends on the scaling coefficient k_O and is inversely proportional to the distance of the obstacle from the vehicle p_O (Equation (6)):

$$U_O(q) = \frac{1}{2} k_o \frac{1}{p_O^n(q)} \tag{6}$$

where

k_O—scaling coefficient for the potential repelling from obstacles;
$p_O(q)$—a distance of the obstacle from point q;
n—exponent $n = 2 \ldots 4$.

Another important factor affecting the driver is the position of the vehicle (distance) in relation to the edges of the roadway p_{BL} and p_{BL}. In this respect, the behaviour of the driver may also be influenced by the type of road edge and the type of roadside; hence, the k_{Bj} coefficient may be different. For a driver travelling on a roadway separated from a hard shoulder with a painted line, the influence of the edge will be lesser. In this case, the occurrence of a slight steering error by the driver, resulting in driving out of the road, does not cause any dangerous consequences. However, a lower roadside, barriers, a high kerb, or trees near the road will affect the driver otherwise. In such situations, driving a vehicle out of an assumed lane may result in serious damage to the vehicle or an accident. In this case, the scaling coefficient should therefore be higher. The value of the potential field U_B, repelling from the edge of the roadway, acting on the point q of the vehicle, will be:

$$U_B(q) = \frac{1}{2} k_{BL} \frac{1}{p_{BL}^2(q)} + \frac{1}{2} k_{BR} \frac{1}{p_{BR}^2(q)} \tag{7}$$

where

k_{BL}—scaling coefficient for the repelling potential from the left edge of the road;
k_{BR}—scaling coefficient for the repelling potential from the right edge of the road;
$p_{BL}(q)$—a lateral distance of point q from the left edge of the road;
$p_{BR}(q)$—a lateral distance of point q from the right edge of the road.

A vehicle moving symmetrically in the middle of the right lane will be affected by potential hazards from the left and right edges of the road, and, despite the different distances from the edges, the values of these potentials will be identical in value but will differ in turn. The effect of these potentials, when moving in the middle of the right lane, should not generate the need to change the lateral position of the vehicle (vehicle movement should be stable).

The values of the coefficients taking into account the potential values from the left and right edges of the road will also depend on the width of the road L, because $p_{BL} + p_{BR} = L$.

The following relationship should be fulfilled:

$$k_{BL} \frac{1}{p_{BL}^2(q)} = -k_{BR} \frac{1}{p_{BR}^2(q)} \tag{8}$$

Therefore, if the value of the scaling coefficient k_{BR} is selected (identified), then the k_{BL} value must be dependent on the current distance of the car from the right edge of the roadway, according to the following Formula (9).

$$k_{BL} = -k_{BR} \frac{p_{BL}^2(q)}{p_{BR}^2(q)} \tag{9}$$

When there is a change in the vehicle's position during motion, e.g., due to an obstacle arising or changing position, interactions from the target point, the edge of the road, and the obstacles will change, as seen in Figure 3.

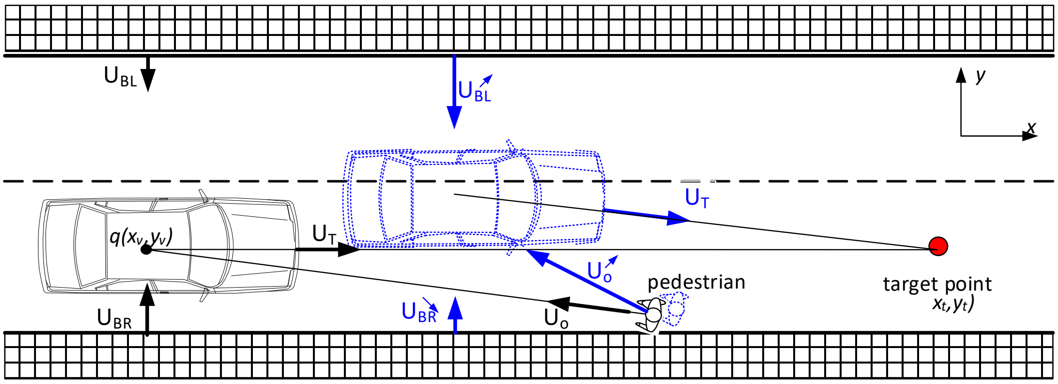

Figure 3. Scheme of changes in interactions.

To ensure that the analysis of the accident situation in Figure 3 does not refer only to the selected material points (vehicle centre of mass, obstacle, and target point), it was decided to introduce the actual size of a vehicle and the safety zone around it and possible obstacles. The safety zone is an area that is larger than the size of the vehicle (or obstacle). The size of the safety zone by which the "overall dimensions" are increased may vary in different directions. A rectangular "Safe Area" was used by Sattel and Brandt [73]. A similar concept of safe "margin" was used in the modified Gipps model [82] and described in the publication of Lee and Huei [57]. Therefore, it can be assumed that a driver, when taking actions in case of an accident hazard, should perform them in such a way so as to obtain a proper sense of safety and he/she should maintain an appropriate, subjectively accepted distance from possible obstacles and the edge of the roadway.

The distance between the vehicle and the obstacle p_o, as related to the centre of mass (x_v,y_v) of the vehicle and (x_o,y_o) of the obstacle, will already be p'_o when the safety zones are applied. This is shown in Figure 4.

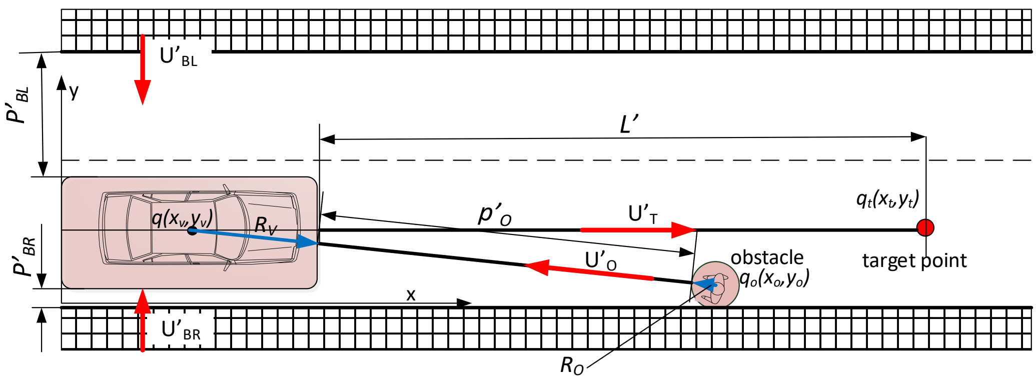

Figure 4. Introduction of vehicle and obstacle safety zones to the situation scheme.

The safety zone around the vehicle may vary in shape. The easiest way to describe and use a rectangular safety zone for a vehicle is to describe and use it as a rectangular safety zone, which, in practice, is an enlarged vehicle size. This may be convergent with the outline of the area that is invisible from the driver's seat [83]. In the case of pedestrians or small obstacles, a safety zone in the form of a circle or an ellipse can be easily applied.

The application of such zones will result in the modification of the previous entries in Equations (5)–(7) in the model.

Therefore, new dimensional parameters will be introduced, which will be:

- L'—the distance between the vehicle safety zone and the target point;
- p'_O—the distance between the vehicle and obstacle safety zones;
- p'_{BR}, p'_{BL}—the distance between the road edges and the vehicle safety zone.

Changing the position of the vehicle relative to the x and y axes will change these distances. To facilitate their definition, it was necessary to determine the distance R_v, which is the distance of the centre of mass of the vehicle from the boundary of the safety zone of the vehicle. A similar distance R_o will occur in the case of a safety zone around an obstacle [36]. The values of potential hazards acting on the vehicle for such determined distances will be as follows:

$$U' = U'_T + U'_O + \sum_{j=1}^{2} U'_{Bj} \quad (10)$$

where

$$U'_T = \frac{1}{2} k_T L'^2 \quad (11)$$

$$U'_O = \frac{1}{2} k_o \frac{1}{p'^n_O} \quad (12)$$

$$U'_B = -\frac{1}{2} k_{BL} \frac{1}{p'^2_{BL}} + \frac{1}{2} k_{BR} \frac{1}{p'^2_{BR}} \quad (13)$$

As the potential forces act on the driven vehicle in a plane (x, y), their values can be separated in the direction of the x-axis (parallel to the road axis) and the y-axis (perpendicular to the road edge), taking into account their turns (see Figure 4). Since the position of the target point is ideally located in the vehicle axis, the effect of the field from the target point in the y-axis direction is 0.

$$U'_x = U'_{Tx} - U'_{Ox} \quad (14)$$

$$U'_y = \overbrace{U'_{Ty}}^{0} + U'_{Oy} + U'_B \quad (15)$$

then

$$U'_x = U'_{Tx} - U'_{Ox} = \frac{1}{2} k_{Tx} L_x'^2 - \frac{1}{2} k_{ox} \frac{1}{p'^n_{Ox}} \quad (16)$$

$$U'_y = \overbrace{U'_{Ty}}^{0} + U'_{Oy} + U'_B = \frac{1}{2} k_{oy} \frac{1}{p'^n_{Oy}} - \frac{1}{2} k_{BL} \frac{1}{p'^2_{BL}} + \frac{1}{2} k_{BR} \frac{1}{p'^2_{BR}} \quad (17)$$

The defined effects of the individual potential fields on the vehicle can be assigned potential values to particular actions of the driver. In accident situations, the driver takes different defensive measures while driving to avoid a possible collision with an obstacle. These consist of two basic defensive manoeuvres, namely avoidance and braking. As shown in many publications, these manoeuvres can be performed simultaneously or separately with different intensities [66,67,84,85].

In the proposed driver model, the driver's action also consists of two activities and will be described by functional sub-models, including:

- deceleration—braking submodel;
- avoiding the obstacle—steering submodel.

The article [85] presents the method of using the potential method to design the control supporting the avoidance of obstacles in the vehicle. The analysed model was used for a simple situation related to avoiding a vehicle on the road, with both edges of the road limited in the form of a wall. In the proposed model, the total potential is the sum of the repulsive potentials, namely from the side wall, from the obstacle, and the goal (target).

The potentials depend on the positions of the vehicle and obstacle in the x and y directions, the distance between the vehicle to the side wall, and the standard deviation of these potentials. The method of determining the potentials differs from the model proposed by the authors. As it was shown in the paper, the coefficients of the model are different for both tested runs, which confirms the need to identify them for different situations and different drivers. The method of developing the avoidance methodology was based on the PID controller modelled on the anticipation model, to which the input signals were the relative angle between the direction of the examinee's vehicle and the reference path as well as deviation between the predicted position and the reference path. In the case of vehicle movement, determining such a path is rather difficult. The personalisation of the system's operation based on the way the manoeuvre is performed by a given driver is debatable. Will such a personalised system improve the way the manoeuvre is performed? What will happen if the role model performs the manoeuvre very incompetently (e.g., a very weak, novice driver, or an elderly person with very little motor skills)?

A similar solution was described in the article [86], but a different road situation was analysed, in which two parked vehicles were used as obstacles. The potential value was defined slightly differently from road edges. Interestingly, also in this case, the coefficients of the model were dependent on the speed of the vehicle.

In turn, in [87], various functions describing the risk potential function were analysed in two road situations: Gaussian, hyperbola, and arctangent. The following parameters were used in the analyses: position and velocities of vehicles, distance from the closest obstacle, and distance within y direction between the obstacle and road edge. Depending on the types of functions used, a different number of parameters were used in the simulation, and at the same time, their values differed.

2.1. The Braking Submodel

A vehicle approaching an obstacle causes an increase in the U'_x potential, associated primarily with the component derived from the impact of the $U'o_x$ obstacle. In this case, however, the value of the w_1 factor should be low enough so that, in a situation where the obstacles move on a "non-collision" track in relation to the vehicle (e.g., a pedestrian walking parallel to the edge of the road), the speed reduction should not take place or should be minor. The increase in U'_y potential, due to the reduction in the distance between the vehicle and obstacle safety zones in the y-axis direction, due to the penetration of the obstacle into the driving area, should result in a possible further reduction in speed, as the greater the change in the U'_y potential (mainly associated with the U'_{Oy} factor), the faster. As a result of a possible avoiding of the obstacle, the potential in relation to the edge of the roadway U'_B may also change. The braking model will take the form of:

$$b(t) = w_1 \cdot U'_x + w_2 \cdot U'_y + w_3 \cdot \frac{U'_y}{dt} \tag{18}$$

where

$b(t)$—vehicle deceleration;
U'_x—potential towards x-axis;
U'_y—potential towards y-axis;
w_1—model coefficient related with potential towards x-axis;
w_2—model coefficients related to potential towards the y-axis, in particular the change of the lateral position between the safety zones of the obstacle and the vehicle;
w_3—model coefficient, related to the rate of change in potential value towards the y-axis, in particular the rate of approach of the safety zones of the obstacle and the vehicle.

The calculated vehicle deceleration will therefore depend on the distance of the safety zones of the vehicle and the obstacle in the x-axis direction, in the y-axis direction, and the rate of these changes.

2.2. The Steering Submodel

The steering submodel takes into account the driver's avoiding of the obstacle using the steering wheel angle δ and depends mainly on the potential in the y-axis direction.

When the vehicle, or more precisely the safety zone of the vehicle, approaches the safety zone of an obstacle in the y-axis direction, the potential U'_y is increased significantly.

$$\delta(t) = w_4 * U'_y + w_5 \frac{U'_y}{dt} \tag{19}$$

where

$\delta(t)$—vehicle steering wheel angle;
U'_x—potential towards x-axis;
U'_y—potential towards y-axis;
w_4—model coefficient related to the potential towards the y-axis;
w_5—model coefficient related to the rate of change in the lateral position of the obstacle–change of potential towards the y-axis.

An increase in the potential along the y-axis U'_y can result in a possible adjustment of the vehicle's position (avoidance manoeuvre) against the steering wheel angle δ. Changing the vehicle's position as a result of avoiding the obstacle also results in a change in the potential in relation to the edge of the road U'_B. As a result of the analyses, it was noted that the value of the steering wheel angle is affected not only by how close the safety zones of the vehicle and the obstacle have approached during driving (in the y axis direction), but also by the speed of these changes. Hence, the component is related to the rate of change in the potential value in the y axis direction. There are driver models (not created based on the method of potential fields), in which there are derivative terms. In robotics, models (created based on the method of potential fields) perform a movement ensuring avoidance of an obstacle, but at low speeds. Preliminary analyses have shown that in the case of cars moving at much higher speeds, adding the term with the time derivative gives better trajectory courses.

3. Simulation Results

For the road situation presented in Figure 4, a computer simulation of the obstacle avoidance manoeuvre and the obtained values of the potential hazard and then the steering wheel angle was carried out.

The simulation verified how the assumed shapes of the safety zone around the analysed objects affect the obtained parameters of potential hazards and the driver's response.

The following parameters were used in the simulation:

- The beginning of the x, y coordinate system is situated on the border of the road and sidewalk;
- The vehicle in its initial position moves in the middle of the right lane—initial position of the vehicle: x_v = 0 m, y_v = 1.5 m;
- Vehicle dimensions: length—4.1 m, width—1.8 m;
- The initial longitudinal speed of the vehicle is assumed to be V_{Lg} = 40 km/h, with the vehicle running parallel to the edge of the roadway, so the lateral speed is assumed to be V_{Lt} = 0 km/h;
- The obstacle (pedestrian) speed is assumed as follows: longitudinal V_{Lg} = 0 km/h, lateral V_{Lt} = 0 ... 3 km/h;
- The obstacle (pedestrian) at the initial moment is in the middle of the sidewalk, at a specified distance from the vehicle x_o = 30 m. The width of the sidewalk is 1 m; hence, the initial position y_o = -0.5 m;
- The width of the roadway is 6 m, and the width of the lane is 3 m.

Examples of dimensions of safety zones around the vehicle and obstacle (e.g., man, dog) are shown in Figure 5.

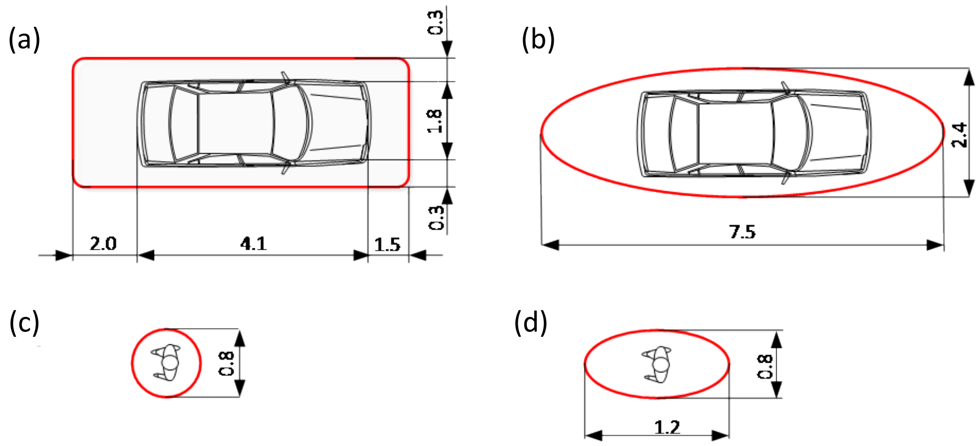

Figure 5. Size of the safety zone dimensions used in the simulation; (**a**) vehicle rectangular, (**b**) vehicle elliptical, (**c**) pedestrian circular, (**d**) pedestrian elliptical.

Figure 6 shows how the value of the radius R_V (see the scheme from Figure 4) changes during a simulated drive for the two selected safety zone shapes around the vehicle.

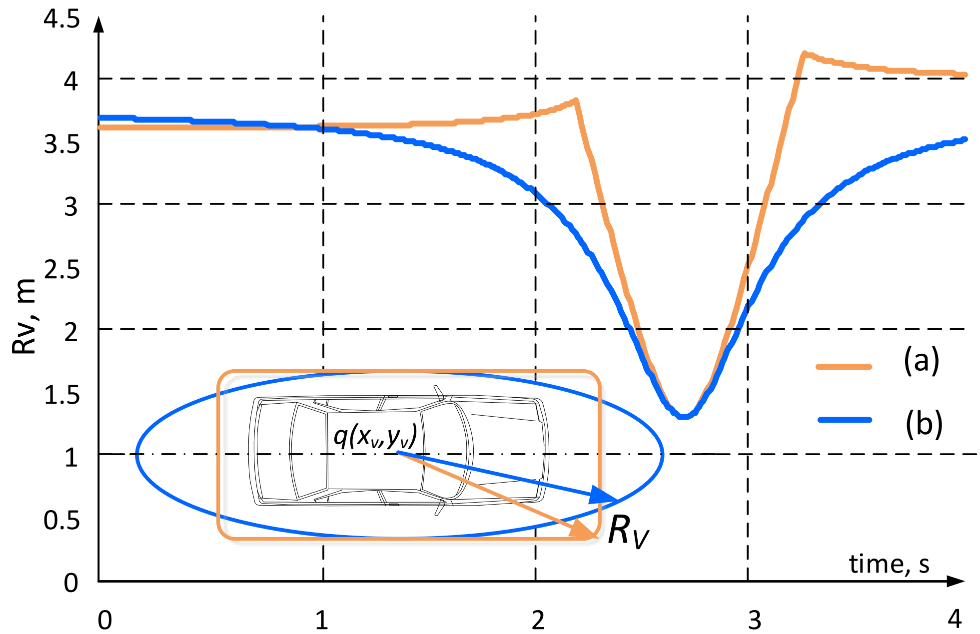

Figure 6. R_V parameter change depending on the shape of the safety zone around the vehicle: (**a**) rectangle, (**b**) ellipse.

As can be seen from the presented scheme, when we are dealing with a safety zone in the form of a rectangle, there are visible sharp refractions of the obtained characteristics, caused by the occurrence of "corners" of the rectangular safety zone. The use of an elliptical-shaped vehicle zone eliminates these.

Figure 7 shows how the value of the distance p'_O (see Figure 4) changes during a simulated drive for different shapes of the vehicles and obstacle safety zones. Four different configurations of safety zone shapes were analysed. It was observed that the shape of the obstacle safety zone (when it is small in relation to the vehicle) has a very slight influence on the change of the p'_O parameter.

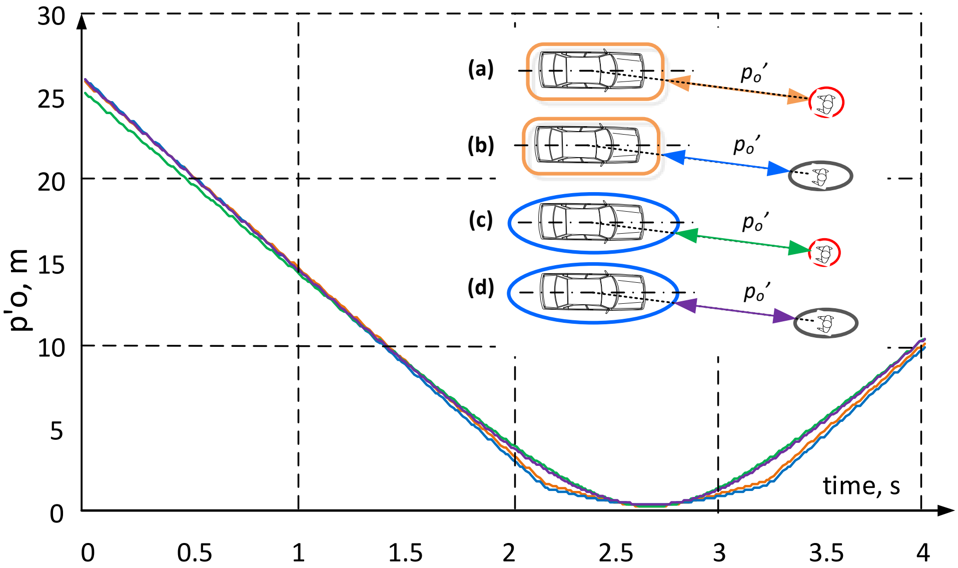

Figure 7. Change of $p'o$ values, depending on the shape of the safety zone around the vehicle and the obstacle: (**a**) vehicle—rectangle, obstacle—circle; (**b**) vehicle—rectangle, obstacle—ellipse; (**c**) vehicle—ellipse, obstacle—circle; (**d**) vehicle—ellipse, obstacle—ellipse.

Figure 8 shows the results of simulations which show how the distance between the safety zones of the vehicle change in the y-axis direction for different zone shapes and different speeds of the lateral movement of the obstacle.

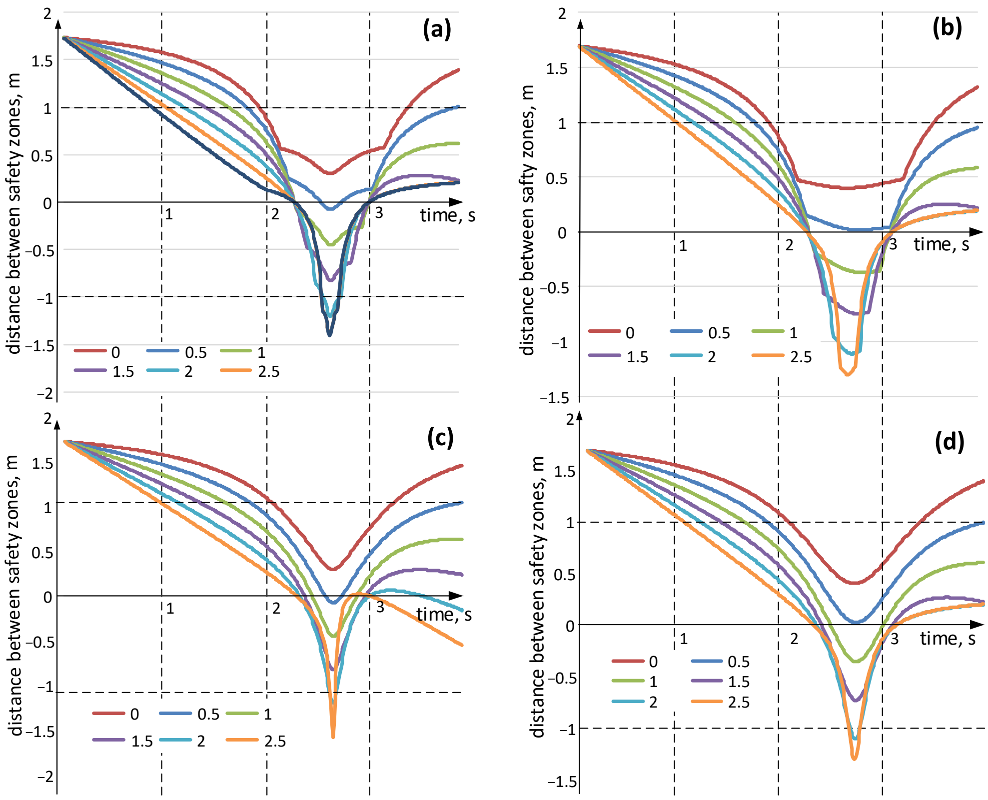

Figure 8. Distance in y-axis direction between safety zones for different lateral speeds (km/h) of the obstacle: (**a**) vehicle—rectangle, obstacle—circle; (**b**) vehicle—rectangle, obstacle—ellipse; (**c**) vehicle—ellipse, obstacle—circle; (**d**) vehicle—ellipse, obstacle—ellipse.

The analysed distance changes in a similar manner, where on schemes from Figure 8, slight refractions, originating in the rectangular shape of the safety zone of the vehicle, are visible. Assuming no change in the vehicle's position in the y-axis direction, the distance between safety zones is reduced with the increase in obstacle speed. In this specific case, there is a maximum speed at which the safety zones will come into contact with each other and, if exceeded, they will interfere with each other. However, what is worth noting is that the shape of the zone affects the progress of changes in this distance. The relatively smoothest progress is obtained when the vehicle and obstacle safety zones are elliptical.

Figure 9 shows an example of a steering wheel angle value obtained in a computer simulation, based on the presented model. The estimation of model coefficients is a complex issue. In order to correctly determine such coefficients, it is necessary to identify the coefficients based on the recorded waveforms for the actual accident situation. In this publication, the model coefficients were selected based on one run. They were initially selected by trial and error, taking into account the research experience of the authors. The main criterion was to obtain a similar course of the steering angle characteristics in relation to the actual course in a similar situation.

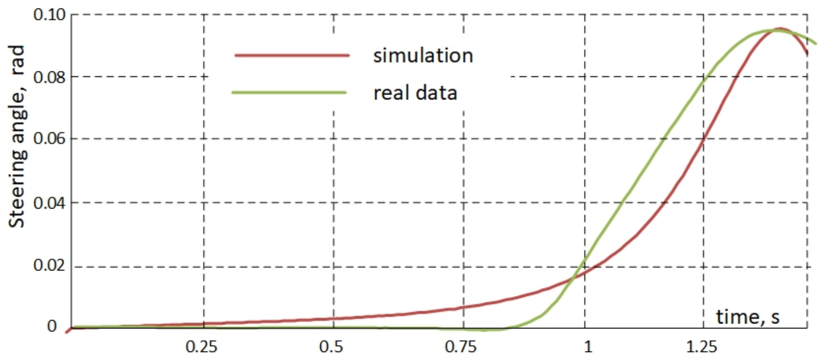

Figure 9. Progress of the steering wheel angle value.

The purpose of their presentation was to present the possibility of obtaining a turning characteristic similar to the characteristics obtained during previous real tests on a car track (Figure 9) [64] for a similar road situations.

The values of the initially adopted parameters for the simulation are presented in Table 1. However, to use this model, it is necessary to perform a full identification of the parameters. It may turn out that the optimal parameters determined for such a situation may not coincide with those determined for a different, more complex situation. While in the case of reconstruction programs it is possible to imagine entering different parameters for different considered situations, it is not possible in assistant systems, when situations change dynamically.

Table 1. Parameters of model used in simulation.

Parameters	Values
W_1	0.0001
W_2	0.00001
W_3	0.0005
W_4	0.002
W_5	0.001

In the simulation, the parameters of the safety zone with an elliptical shape were used. Along with the penetration of an obstacle into the vehicle's driving area, the value of the steering wheel angle gradually increases. After reaching the appropriate inclination of the test vehicle, the stage of decreasing the value of this angle takes place.

4. Discussion and Conclusions

The presented algorithm, describing the method of performance of the obstacle avoidance manoeuvre in a simulated simple road situation, confirms the adopted assumptions of the model.

The used steering model is based on the analysis of the relative position of the obstacle to the vehicle. On this basis, the potential value, which is the basic parameter for determining the driver's response, is determined. Therefore, this model may in the future be used in simulation programs involving the reconstruction of road accidents. Such a model can also be used in programs to reconstruct road accidents and analyse vehicle motion, taking into account the driver's behaviour in these situations. The driver model enables the analysis of vehicle traffic limits and obstacles for which a safe bypassing of the obstacle may not be possible.

In the reconstruction procedure, the mutual position of the various obstacles is known in principle, so it is possible to take into account the specific geometrical parameters of the situation. The analysed article presents the concept of a simple accident situation with a pedestrian, but in the future, it is planned to consider more complex situations. However, to use this model, it is necessary to perform a full identification of the parameters. The same should be conducted for other scenarios of accident situation, because it may turn out that the optimal parameters determined for such a situation may be different than for another, more complex situation [87]. While in the case of reconstruction programs, various parameters can be entered as input data for different considered situations, in assistive systems, when road situations change dynamically, this is not possible. The basic problem, however, is whether it will be possible to adequately represent more complex models with identical parameters (coefficients). Unfortunately, taking into account the history of creating mathematical models, most of them are dedicated to specific purposes—road situations. In most publications, slightly changed test conditions can cause changes in the field coefficients. By creating different versions of the model for reconstruction programs, the appropriate coefficients recommended for a specific road situation may be used. In terms of creating a model for more complex situations (obstacles coming from the opposite direction or penetrating from the left side of the road), work is being carried out to develop initial assumptions for these models.

However, in this work, the authors wanted to present the concept of using the potential method in cars, which differs from the classic approach used in robotics.

As mentioned earlier, this is not the only possibility when using the model. Taking into account the fact that currently various optical, ultrasonic, or laser sensors are commonly used in vehicles, which can determine the position of possible obstacles to the vehicle with very high accuracy, it is possible to use the presented algorithm in real devices supporting the driver's work.

Given the universality of systems that analyse the location of other objects around the vehicle, it can be considered that the proposed algorithm may be a step in creating new driver-assistant algorithms in the future. It is possible that computer systems enabling real-time analyses of the driver's location can enable the use of similar algorithms for autonomous driving. The planned use of the model are programs for the reconstruction of road accidents, and only after appropriate validation and verification of the model for various parameters of the situation can they be a premise for developing a model for the assistant system. Of course, one should be aware that assistant systems cannot provide full protection in traffic. The presented results illustrate the possibilities of the proposed model. We are aware that further work is needed to fully verify the model, including in terms of driver comfort.

As shown in the works of many authors, in most cases of accident situations, the drivers can use the manoeuvres of avoiding obstacles and braking. Therefore, the presented steering model will be complemented by a braking model, to provide a comprehensive proposal of the driver's actions in case of an accident risk. The model is still under development. Verification procedures will be developed for the detailed determination of model coefficients. Further work is expected to verify the model for various, much more complex scenarios with the use of several vehicles and obstacles. Works on improving the model will continue.

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