*designs*

MDPI

*Article*

# Performance Assessment in a "Lane Departure" Scenario of Impending Collision for an ADAS Logic Based on Injury Risk Minimisation

**Michelangelo-Santo Gulino [1,*], Dario Vangi [1] and Krzysztof Damaziak [2]**

[1] Department of Industrial Engineering of Florence, Università degli Studi di Firenze, Via di Santa Marta 3, 50139 Firenze, Italy
[2] Faculty of Mechanical Engineering, Institute of Mechanics and Computational Engineering, Military University of Technology, Gen. Sylwestra Kaliskiego Street 2, 00-908 Warsaw, Poland
* Correspondence: michelangelosanto.gulino@unifi.it

**Abstract:** The current prioritisation of road safety enhancement in the automotive sector is leading toward the near future implementation of Advanced Driver Assistance Systems (ADASs), aiming at the simultaneous intervention of braking and steering for impact avoidance in case of an impending collision. However, it is partially unclear how new technologies for controlling the steering will actually behave in the case of inevitable collision states; the need consequently emerges to propose and tune efficient ADAS strategies to handle the complexity of critical road scenarios. An adaptive intervention logic on braking and steering for highly automated vehicles is applied in the context of a "lane departure", two-vehicle critical road scenario; the ADAS implementing the logic activates to minimise the injury risk for the ego vehicle's occupants at each time step, adapting to the eventual scenario evolution consequent to actions by other road users. The performance of the adaptive logic is investigated by a software-in-the-loop approach, varying the mutual position of the involved vehicles at the beginning of the criticality and comparing the injury risk outcomes of the eventual impacts with those connected to the Autonomous Emergency Braking (AEB). The results highlight a twofold benefit from the adaptive logic application in terms of road safety: (1) it decreases the frequency of impacts compared to the AEB function; (2) in inevitable collision states, it decreases injury risk for the vehicles' occupants down to 40% compared to the AEB. This latter condition is achieved thanks to the possibility of reaching highly eccentric impact conditions (low impact forces and occupants' injury risk as a consequence). The obtained highlights expand the literature regarding the adaptive logic by considering a diverse critical road scenario and investigating how fine variations on the vehicles' mutual position at the beginning of the criticality reflect on the injury outcomes for different types of intervention logic.

**Keywords:** steering; braking; impact eccentricity; velocity change ($\Delta V$); impact closing speed

check for updates

**Citation:** Gulino, M. S.; Vangi, D.; Damaziak, K. Performance Assessment in a "Lane Departure" Scenario of Impending Collision for an ADAS Logic Based on Injury Risk Minimisation. *Designs* **2023**, *7*, 59. https://doi.org/10.3390/designs7030059

Academic Editors: Hua Wei, Guiling (Grace) Wang and Branislav Dimitrijevic

Received: 17 March 2023
Revised: 3 April 2023
Accepted: 18 April 2023
Published: 25 April 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The European automotive industry is currently deploying considerable resources in vehicle development to increase safety for occupants and other road users. The most apparent results are summarised in Eurostat data (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_accident_fatalities_-_statistics_by_type_of_vehicle, accessed on 15 March 2023), which show a 30% reduction in fatal road accidents over the decade 2009–2019. This improvement can be attributed to several factors, one of which is the decrease in the occurrence of all types of impact. This is primarily due to the implementation of in-vehicle Advanced Driver Assistance Systems (ADASs) such as Lane Keeping Assist (refer, for instance, to [1,2]), Adaptive Cruise Control (as reported by [3,4]), Forward Collision Warning (as in [5]), or Autonomous Emergency Braking (AEB, refer, for instance, to [6]), which frequently allow complete avoidance of impact and whose effectiveness increases as market penetration increases. In Inevitable Collision States (ICSs, as indicated by [7]) involving multiple vehicles, a further factor is the ability to reduce Injury Risk (IR) for the vehicle occupants, e.g., by modifying the closing speed between vehicles at the collision instant ($V_r$) through the deceleration provided by an AEB. This type of scenario is becoming more and more relevant as technology progresses—even if highly automated vehicles are capable of predictively adapting their actions to avoid conditions of possible conflict with other vehicles, it must be considered that the average age of the European circulating fleet of passenger cars is 11.8 years (https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/, accessed on 15 March 2023). This implies that the future road environment will see the coexistence of vehicles with diverse levels of automation, with the possible occurrence of unexpected conflicts for the autonomous system caused by the absence (or limited presence) of ADAS on board other vehicles involved in the critical situation; possible scenarios where the driver intervenes diversely from what is prescribed by an ADAS device should also be foreseen.

Although $V_r$ contributes substantially to IR in ICSs, it is not the sole parameter influencing IR. According to a well-established model by [8], IR for vehicle occupants is a function of several parameters related to the impact configuration, in particular, the area of intrusion (frontal, rear, or lateral) and the translation velocity change sustained by the vehicle during the impact ($\Delta V$, directly linked to the acceleration experienced by occupants). From recent studies by [9,10], it emerges, however, that $V_r$ is only one contribution to $\Delta V$, which also depends on the eccentricity of the impact according to [11]: the higher the eccentricity, the lower the resulting $\Delta V$ value since a leading part of the impact energy will be converted into vehicle rotation rather than translation. It follows that, although the actuation of a system such as the AEB guarantees a significant decrease in $V_r$ compared to the case of no intervention, there is the chance that a braking intervention will result in low eccentricity impacts with a high $\Delta V$ value. From this standpoint, the possibilities provided by new steer-by-wire technologies (as those analysed by [12]) for the automatic activation of emergency steering would enable increasing impact eccentricity, lowering $\Delta V$ and IR as a consequence. While the possibilities associated with autonomous emergency steering are being evaluated within EuroNCAP for the introduction of ad hoc test protocols for ADASs. (https://cdn.euroncap.com/media/30700/euroncap-roadmap-2025-v4.pdf, accessed on 15 March 2023), there is currently no indication of how these technologies will be implemented in vehicles marketed by OEMs in the near future for the management of emergency situations such as ICSs [13].

In a previous study [14], the authors illustrated the possibility of introducing braking and steering intervention logic for ADASs based on the minimisation of IR, called “adaptive”, as it is able to modify its intervention according to possible evolutions of the scenario caused by actions of other road users. The system was tested in a software-in-the-loop environment in intersection-related ICS scenarios, considering three specific opponent driver behaviours and positions of the two vehicles involved in the criticality; the work demonstrated that such an adaptive logic produces advantages in terms of resulting IR compared to intervention through AEB only. The initial positions of the two vehicles immediately corresponded to an ICS since the time to collision (TTC) was close to 1 s, and it was assumed that the ADAS was capable of recognising the opponent only starting from the initial instant (due to limited ADAS sensor vision capabilities, such as in [15] or presence of visual obstacles); considering a generic road environment, the ADAS system is capable of identifying the opponent at instants prior to the initial one, with the possibility of completely preventing the conflict.

The present work advances state-of-the-art methods regarding the adaptive logic by rigorously addressing a scenario differing from the one already presented, i.e., a scenario of lane departure by the opponent vehicle rather than an intersection-related conflict. In particular, in previous studies, three initial X–Y positions of the opponent were exemplarily specified, corresponding to three instants when the ADAS onboard the ego vehicle recognised the opponent. Nevertheless, the initial positions can significantly affect the interventions that the adaptive logic can perform to minimise IR for the occupants; if the opponent is farther, the TTC is higher, giving the ADAS more margin to more effectively activate the X-by-wire circuits to limit injury consequences. For this reason, detailed highlights are provided here regarding how fine variations in vehicle position at the onset of criticality alter the outcomes of activation by the adaptive logic, both in terms of IR minimisation in ICSs and impact avoidance.

## 2. Materials and Methods

### *2.1. Model-in-the-Loop*

The software-in-the-loop environment used for the study is described in detail by the authors in a previous article [14], as is the adaptive logic to be simulated. Figure 1 illustrates the functioning of the ADAS system in a simulated environment, in terms of Model-in-the-Loop (MiL, as reported by [2]) considering the performed modifications compared to what is already included in previous research:

1. Through sensors and data fusion [16,17], the system onboard the ego vehicle acquires the position, translation speed, heading, and angular velocity of the opponent, employing these elements to perform a prediction of intention [18] on the opponent's actions; the time step at which the system acquires supplementary information from the sensors is set equal to 0.1 s in the present study.
2. Starting from the sensor information and the predicted intention of the opponent, the adaptive system evaluates whether the collision is avoidable without intervening by braking or steering, adopting a Reduced Order Dynamic Model (RODM) discussed in previous articles [19,20] for the accurate 2D simulation of free kinematics and collision phases. Considering the low TTC in the analysed scenarios that is below the usual human time for reaction, the ADAS system has no possibility to alert the driver for intervention; the responsibility for intervention hence falls on the ADAS alone. If the collision is avoidable, the system does not intervene and bypasses the point 3 reported below.
3. If the collision occurs should no intervention by the ADAS be performed, the system evaluates the outcomes associated with 35 combinations of wheel steering and braking through RODM simulations; the levels of wheel steering vary between 0° and 9° in steps of 3° (grip limit for 50 km/h) to the right and left (negative and positive steering, respectively), while the braking value varies between 0% and 100% (corresponding to decelerations of 8 $m/s^2$). Each combination is associated with an IR value, equal to IR itself if the intervention results in a collision and to the clearance between vehicles (minimum distance reached during kinematics) if the collision does not occur. The clearance is associated with negative IR values.
4. The adaptive system is capable of identifying the best intervention on steering and braking by searching for the minimum IR value among all the identified outcomes, which can be graphically summarised in an IR map such as the one shown in Figure 1. In this way, the adaptive logic is able to handle both avoidable and unavoidable collision states; for the present study, the decision logic considers the IR for the occupants of the ego vehicle only.
5. Steering and braking are adopted, and the vehicles move to the next time step for scanning the external environment by the ego vehicle's sensors. For ease of discussion, it is assumed that the braking and steering system circuits activate instantaneously (actual values for a braking system are close to 0.2 s).
6. The ADAS assesses whether, compared to the previous step of scanning the environment, the vehicles' centres of gravity are distancing; in the latter case, the vehicles have exited the criticality, and it is no longer necessary to simulate further time steps. Otherwise, the steps are repeated using the vehicles' new positions, translation, and rotational velocities.

From the description of this iterative process, it is possible to deduce the motivation behind the adaptive classification of the logic under investigation: at each new time step, the ADAS implementing the logic is able to act on braking and steering for adapting to possible changes in the scenario caused, for example, by the behaviour of the opponent's driver. Since for each scanning time step of the scenario (0.1 s) the system identifies the outcomes associated with 35 different possible interventions on braking and steering, the results reported below for the adaptive logic derive from a number of simulations exceeding 5000. The considered time step stands as sufficient for a real-time implementation of the logic; as an alternative, a pre-compiled database including the outcome for each intervention on braking/steering in a large amount of scenarios can be used to directly retrieve the best intervention in specific road scenarios. In the case of AEB, a logic that can also be investigated in the same software environment, at the above-described point 3, the ADAS is capable of activating only the degree of braking using an unmodulated value of 100% (braking at 8 $m/s^2$).

While the ego vehicle can rely on LiDAR/RaDAR and cameras for the identification of the opponent's features such as speed, heading, and geometry, it can also derive an accurate indication of its current state by several sensor-based strategies: the most novel technologies consider data fusion among information from Global Navigation Satellites Systems (GNSSs), Inertial Measurement Units (IMUs), and cameras, being able to accurately command the vehicle also in the case of GNSS signal outages (up to 20 s) [21], or compensate for systematic errors in the measurement chain [22]. By combining information from these sensors and a state observer as the Kalman filter, vehicle dynamics can also be monitored and piloted by precise estimation on the instantaneous sideslip angle [23–26].

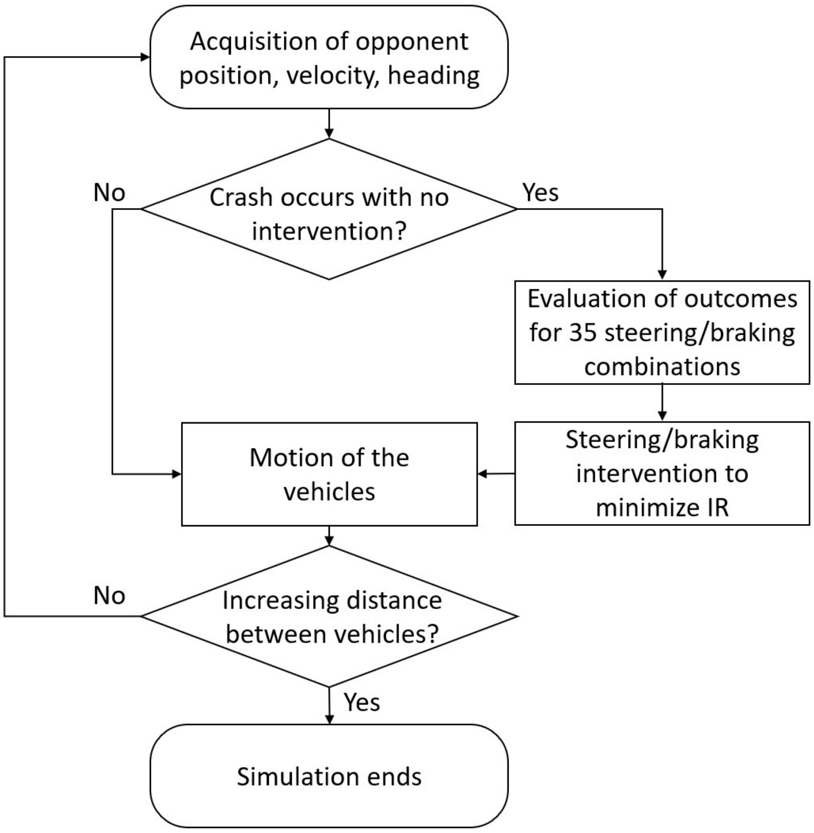

**Figure 1.** Flow diagram for the adaptive logic activation.

### 2.2. IR Model

The model in Figure 2 based on the injury indicator Maximum Abbreviated Injury Scale equal or greater than 3 (MAIS 3+) is used to assess the risk of injury to vehicle occupants, where it is a function of the area of intrusion and the velocity change sustained by the single vehicle during the impact $\Delta V$. In this modelling, the most severe types of impact for the occupants at equal $\Delta V$ are those where the area of intrusion is in correspondence of the compartment on the same side of an occupant seating position ("near side" impact); in descending order of severity, impacts to all other side areas ("side" impact), front ("front" impact), and rear regions ("back" impact) are sequentially found. The ADAS intervention can modify both $\Delta V$ and impact type at the same time. In this study, it is assumed that there are occupants in the vehicle positioned on both the right and left side of the vehicle, so that impacts on the compartment are always classified as "near side" impacts.

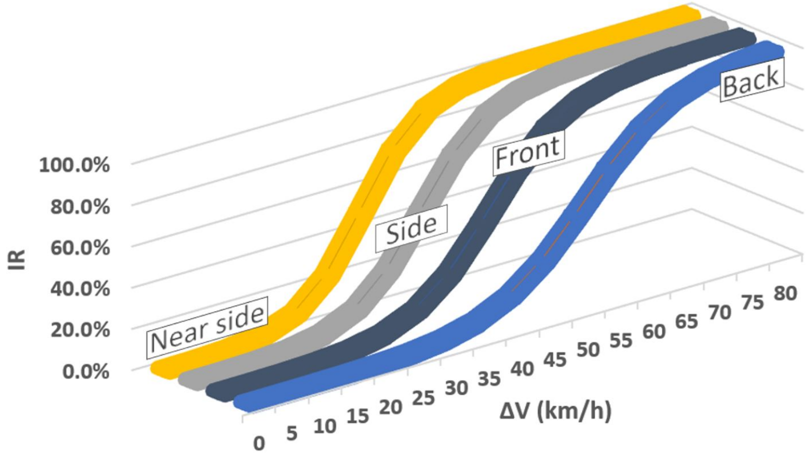

**Figure 2.** IR model employed in the present study, where IR is a function of the location of the intrusion area, seating position of the occupant, and $\Delta V$.

### 2.3. Case Study Scenario

The case study considered for the performance assessment of the adaptive logic is schematised in Figure 3. The two participating vehicles are on a straight two-way road, with carriageway separations by broken lines, and are moving at a speed of 50 km/h. At the initial instant of the critical scenario, the centre of gravity of the opponent vehicle is at a distance $Y_a$ from the centre of gravity of the ego vehicle; the driver of the opponent vehicle steers to his/her left from 0° to +9° in 0.3 s (typical behaviour of drivers in this type of accident scenario according to [27]), invading the adjacent lane in the opposite direction of travel. Considering a lane with a typical width of 3.6 m, the mutual distance between vehicles in the transverse direction to the roadway axis $X_a$ is considered to be 3.5 m and 4 m in two separate studies (to consider a non-preferential occupation in the lane by the ego vehicle). The vehicles are identical in terms of geometry and mass, with a length of 4.2 m and a mass of 1200 kg. At the environmental level, no visual obstructions are present that can compromise the correct recognition of the opponent by the ADAS sensors; it is also assumed that the sensors are able to identify the kinematic characteristics of the opponent, whichever its position on the road (no field-of-view constraints).

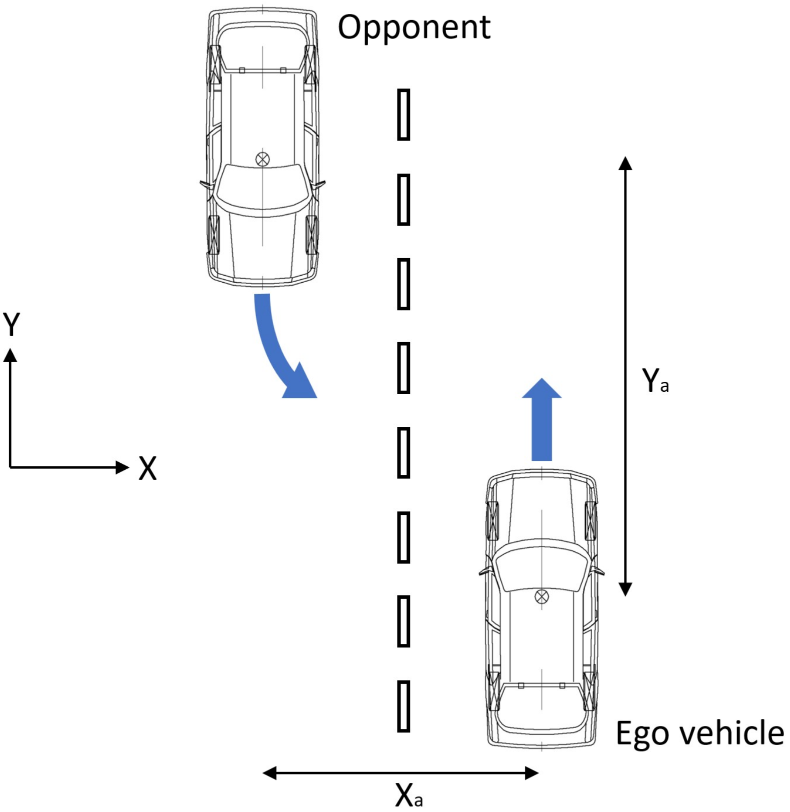

**Figure 3.** Synthetic representation of the considered lane departure case study.

## 3. Results

Table 1 shows the results of software-in-the-loop simulations, varying $Y_a$ at the beginning of the criticality, for an $X_a$ distance equal to 3.5 m and for three diverse types of logic: no intervention, AEB, and adaptive logic. The reported IR values are those related to the final impact configuration. The "no intervention" case represents the reference scenario (refer to [28]), i.e., the baseline usually considered for ADAS performance assessment. The reported $Y_a$ values correspond to those for which at least one logic leads to an impact. It can be marked that the intervention by an AEB function is convenient for any $Y_a$ value compared to the "no intervention" logic. The frequency of impacts in terms of spatial range is highest for the case of "no intervention", with impacts associated with high IR values up to 82.5% for both vehicles. The AEB logic reduces the spatial range of impact occurrence from 21 m to 13 m, with lower associated IR values and a maximum IR value of 34.5%. The adaptive logic provides a twofold advantage for the increase of road safety in this scenario compared to both the above-mentioned types of logic, as it contributes to the decrease of both the spatial range in which collisions occur (12 m) and of IR associated with the single accident event; the maximum IR value for the involved vehicles is 2.4%. A comparison between AEB and the adaptive logic for the same values of $Y_a$ shows that the adaptive logic tends to generate "near side" impacts for the ego vehicle; even if this type of impact is associated with maximum IR values at equal $\Delta V$ based on Figure 3, in this case, the adaptive system intervenes on braking and steering to direct the ego vehicle towards eccentric impact configurations with reduced $\Delta V$. Overall, the use of the adaptive logic reduces IR by up to 32% compared to an AEB and by 80% compared to the "no intervention" logic. Considering all the scenarios, the average values for "no intervention", AEB, and adaptive logic are 28.0%, 14.0%, and 1.4% for the ego vehicle, respectively. Slightly different IR results are obtained for the opponent because of differences in impact types, with average IR values of 28.0%, 12.8%, and 0.6% for the opponent in case of "no intervention", AEB, and adaptive logic, respectively; nonetheless, these data demonstrate the capabilities of the adaptive logic to increase the safety for the occupants of both the involved vehicles, despite the adaptive ADAS being designed to minimise, at each time step, IR for the ego vehicle's occupants only.

Table 2 shows the results for the case of $X_a$ = 4 m. Due to the greater transversal distance between vehicles, collisions occur in a narrower spatial range than in the case of $X_a$ = 3.5 m; the ADAS systems have a higher temporal margin of intervention to recognise the criticality and prevent the collision, and the spatial range of collision occurrence is the same for the AEB and the adaptive logic (11 m). The global analysis of the data provides average IR values for the "no intervention", AEB, and adaptive types of logic, respectively equal to 25.7%, 12.5%, and 0.9% for the ego vehicle, lower than the case of $X_a$ = 3.5 m. For the AEB logic, a maximum value of 41.5% is obtained for the ego vehicle, higher than that in the case of $X_a$ = 3.5 m because of a lower eccentricity of the impact at the same $V_r$. Transversely, it can be noted that the AEB provides worse results than the "no intervention" logic in a few specific cases, such as when $Y_a$ ranges between 31 m and 37 m. Conversely, comparing the "no intervention" logic with the adaptive logic, it can be seen that the latter provides higher IR values only when $Y_a$ ranges between 31 and 33 m (0.2–0.7% vs. 0.1–0.5%); however, the IR values are less than 1% for these values of $Y_a$. Similarly to the case of $X_a$ = 3.5 m, also for $X_a$ = 4 m, the ability of the adaptive logic to reduce IR for the occupants of both vehicles is derived.

Figure 4 summarises the braking and steering interventions by the adaptive logic when $Y_a$ varies, as a function of the TTC and for $X_a$ = 4 m. The system always tries to steer to the right (negative steering angles) and rarely to brake, except in the last moments before the collision (low TTCs); the possibility of insisting on the steering degree allows extremely eccentric crash conditions with a reduced $\Delta V$ to be reached, despite the fact that $V_r$ remains almost identical to the relative speed between vehicles at the beginning of the criticality if no braking is applied. The priority for the system is therefore to steer for piloting the ego vehicle towards eccentric impact conditions and only then to decrease the speed of the ego vehicle to reduce $V_r$; this is also in line with the typical reaction of a driver in correspondence of this type of scenarios, according to [29].

From the results obtained by the software-in-the-loop simulations, further highlights can be finally reported compared to previous literature on the adaptive logic:

1. The additional activation on steering by the adaptive logic leads to a relevant decrease in IR, both compared to the "no intervention" logic ($-80\%$) and to the AEB function ($-30\%$) ; these values are significantly higher than those associated with intersection collisions [14].
2. The adaptive logic does not increase the frequency of impacts compared to the AEB function, also leading to its decrease if a limited distance between vehicles is addressed along the transversal to the road axis.
3. The interventions to be prioritised to reduce IR are those on the steering, so that the vehicle can be guided towards eccentric impacts; the intervention on the braking can bring advantages when the TTC is low, i.e., when the vehicles are already moving towards eccentric impacts and decreasing the closing speed results in a reduction of $\Delta V$.
4. Although the activation of the braking and steering for the adaptive logic is aimed at minimising the IR for the occupants of the ego vehicle, a reduction of $\Delta V$ for the occupants of both vehicles is confirmed, compared to both the case of "no intervention" and AEB function.

**Table 1.** Simulation outcomes in terms of IR and impact type for the two vehicles, based on the considered activation logic as a function of $Y_a$ and for $X_a$ = 3.5 m ("-" means that the impact has been avoided).

| **3.5** | **NO INTERVENTION** | | | | **AEB** | | | | **ADAPTIVE** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ya** | **IR Ego [%]** | **IR Opp [%]** | **Impact Type Ego** | **Impact Type Opp** | **IR Ego [%]** | **IR Opp [%]** | **Impact Type Ego** | **Impact Type Opp** | **IR Ego [%]** | **IR Opp [%]** | **Impact Type Ego** | **Impact Type Opp** |
| 26 | 0.2 | 0.2 | Near Side | Side | - | - | - | - | - | - | - | - |
| 27 | 0.3 | 0.4 | Near Side | Side | - | - | - | - | - | - | - | - |
| 28 | 0.6 | 0.7 | Near Side | Side | 0.2 | 0.1 | Near Side | Side | 0.1 | 0.1 | Side | Side |
| 29 | 0.9 | 0.9 | Side | Front | 0.7 | 0.3 | Near Side | Front | 0.2 | 0.1 | Side | Front |
| 30 | 3.2 | 2.5 | Side | Front | 1.2 | 0.4 | Near Side | Front | 0.8 | 0.3 | Near Side | Front |
| 31 | 21.7 | 13.6 | Side | Front | 3 | 1.5 | Side | Front | 0.9 | 0.3 | Near Side | Front |
| 32 | 63.6 | 46.3 | Side | Front | 16.7 | 6.7 | Side | Front | 2.4 | 0.8 | Near Side | Front |
| 33 | 56.9 | 63.1 | Front | Front | 26.1 | 24.7 | Front | Front | 1.8 | 0.6 | Near Side | Front |
| 34 | 31.6 | 32.9 | Front | Front | 23.6 | 32.1 | Front | Front | 1.1 | 0.4 | Near Side | Front |
| 35 | 77 | 77.9 | Front | Front | 31.6 | 34.2 | Front | Front | 1.8 | 0.6 | Near Side | Front |
| 36 | 82.4 | 83 | Front | Front | 34.5 | 31.5 | Front | Front | 2.2 | 0.7 | Near Side | Front |
| 37 | 82.5 | 81.9 | Front | Front | 33.8 | 29.9 | Front | Front | 2.1 | 0.7 | Near Side | Front |
| 38 | 52.3 | 49.4 | Front | Front | 17.3 | 13.6 | Front | Front | 1.1 | 0.7 | Near Side | Front |
| 39 | 76.9 | 75.9 | Front | Front | 5.6 | 3.1 | Front | Front | 1.6 | 0.9 | Near Side | Front |
| 40 | 21.2 | 19.5 | Front | Front | 0.9 | 0.4 | Front | Side | 2.4 | 1.4 | Near Side | Front |
| 41 | 23.8 | 41.8 | Front | Side | 0.2 | 0.2 | Front | Near Side | - | - | - | - |
| 42 | 14.8 | 18.7 | Front | Side | - | - | - | - | - | - | - | - |
| 43 | 3.7 | 2.5 | Front | Side | - | - | - | - | - | - | - | - |
| 44 | 1.4 | 2.4 | Front | Near Side | - | - | - | - | - | - | - | - |
| 45 | 0.6 | 1.1 | Front | Near Side | - | - | - | - | - | - | - | - |
| 46 | 0.3 | 0.4 | Front | Near Side | - | - | - | - | - | - | - | - |
| 47 | 0.1 | 0.1 | Front | Side | - | - | - | - | - | - | - | - |

**Table 2.** Simulation outcomes in terms of IR and impact type for the two vehicles, based on the considered activation logic as a function of $Y_a$ and for $X_a$ = 4 m ("-" means that the impact has been avoided).

| **Xa = 4 m** | **NO INTERVENTION** | | | | **AEB** | | | | **ADAPTIVE** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ya** | **IR Ego [%]** | **IR Opp [%]** | **Impact Type Ego** | **Impact Type Opp** | **IR Ego [%]** | **IR Opp [%]** | **Impact Type Ego** | **Impact Type Opp** | **IR Ego [%]** | **IR Opp [%]** | **Impact Type Ego** | **Impact Type Opp** |
| 31 | 0.1 | 0.1 | Side | Front | 0.2 | 0.2 | Near side | Front | 0.2 | 0.2 | Side | Side |
| 32 | 0.3 | 0.2 | Near side | Front | 0.9 | 0.3 | Near side | Front | 0.5 | 0.2 | Side | Side |
| 33 | 0.5 | 0.3 | Near side | Front | 2.6 | 0.8 | Near side | Front | 0.7 | 0.3 | Near side | Front |
| 34 | 0.9 | 0.6 | Near side | Front | 15 | 6 | Side | Front | 0.2 | 0.1 | Side | Front |
| 35 | 1.6 | 1.5 | Side | Front | 22.6 | 20.9 | Front | Front | 1 | 0.4 | Near side | Front |
| 36 | 9.2 | 6.7 | Side | Front | 24.1 | 21.9 | Front | Front | 1.3 | 0.5 | Side | Front |
| 37 | 29.1 | 38.9 | Front | Front | 41.5 | 38.3 | Front | Front | 1.8 | 0.6 | Near side | Front |
| 38 | 48 | 54.4 | Front | Front | 27.9 | 25.3 | Front | Front | 1.3 | 0.5 | Near side | Front |
| 39 | 34.3 | 35.4 | Front | Front | 8 | 6.5 | Front | Front | 0.8 | 0.3 | Near side | Front |
| 40 | 83.4 | 83.3 | Front | Front | 6.4 | 4.3 | Front | Front | 0.2 | 0.2 | Side | Front |
| 41 | 78.6 | 78.5 | Front | Front | 0.8 | 0.5 | Front | Side | 1 | 0.4 | Near side | Front |
| 42 | 78.2 | 77.6 | Front | Front | 0.2 | 0.2 | Front | Near side | 2.3 | 0.8 | Near side | Front |
| 43 | 80.2 | 77.9 | Front | Front | - | - | - | - | - | - | - | - |
| 44 | 27.5 | 26 | Front | Front | - | - | - | - | - | - | - | - |
| 45 | 52.4 | 73.5 | Front | Front | - | - | - | - | - | - | - | - |
| 46 | 10.8 | 9.6 | Front | Side | - | - | - | - | - | - | - | - |
| 47 | 2.9 | 4.3 | Front | Near side | - | - | - | - | - | - | - | - |
| 48 | 1.2 | 2.2 | Front | Near side | - | - | - | - | - | - | - | - |
| 49 | 0.5 | 0.9 | Front | Near side | - | - | - | - | - | - | - | - |
| 50 | 0.2 | 0.1 | Front | Side | - | - | - | - | - | - | - | - |
| 51 | 0.1 | 0.1 | Front | Side | - | - | - | - | - | - | - | - |

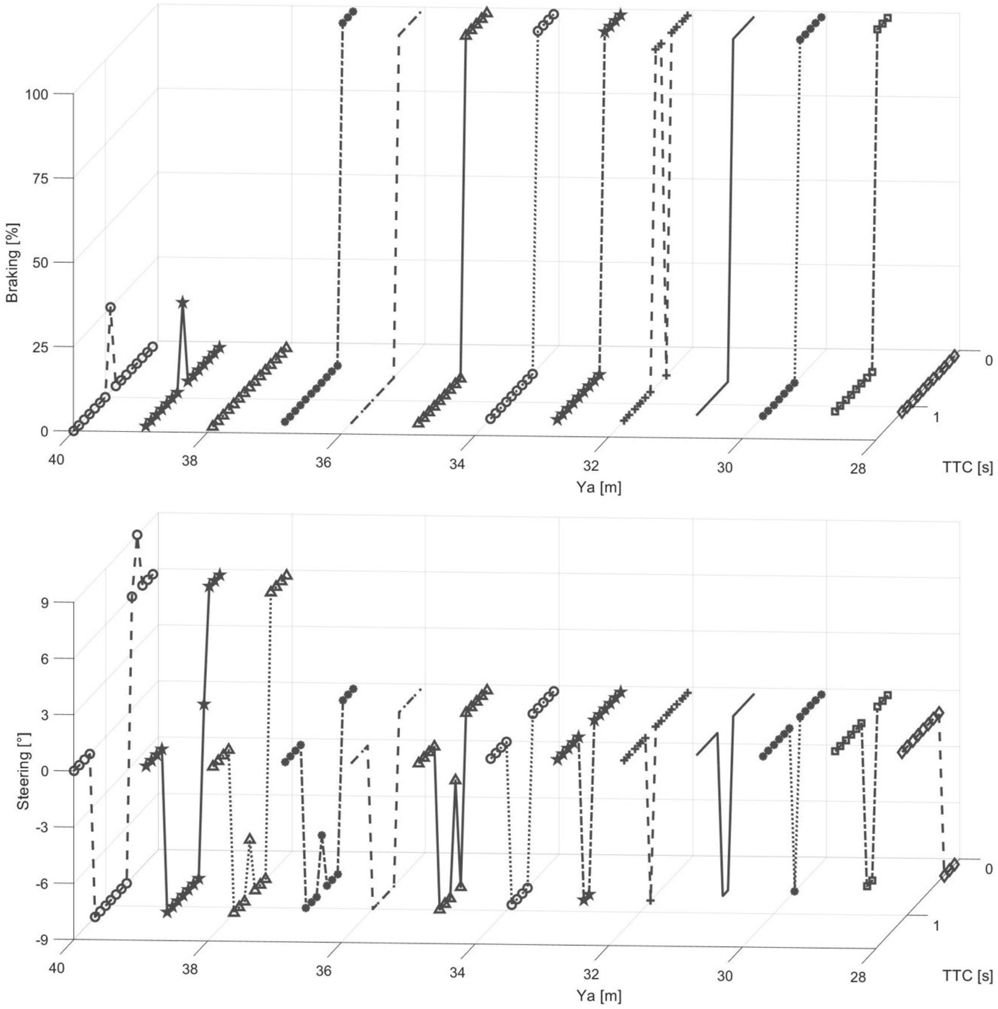

**Figure 4.** Trend in steering and braking intervention by the adaptive logic as a function of $Y_a$ ($X_a$ = 4 m).

## 4. Conclusions

The present study aimed at evaluating, in a software environment, the performance of an adaptive braking and steering intervention logic for ADASs based on the instantaneous minimisation of Injury Risk (IR) in a lane departure scenario. By investigating the influence of parameters related to the mutual position of vehicles at the beginning of the criticality, the study showed this type of logic provides for a twofold advantage in terms of road safety compared to a classic AEB intervention logic: (1) the spatial range in which collisions occur (frequency of impacts) decreases when employing the adaptive logic, (2) the IR values associated with the considered cases of inevitable collision is reduced. In absolute terms, the adaptive logic leads to a reduction of IR up to 40% compared to the case of AEB, while the average value of IR is reduced up to 12%, considering all possible relative positions between vehicles at the beginning of the criticality. The adaptive logic chiefly intervenes by steering rather than by braking: the system is capable of piloting the ego vehicle towards extremely eccentric impact configurations that are, by their nature, associated with a low value of velocity change sustained by the vehicle during the impact (directly correlated to IR); this enables the achievement of greater benefits compared to the sole reduction in closing speed, guaranteed by a classic AEB logic in terms of IR for the occupant of both the ego vehicle and the opponent. The present work hence expands the knowledge on the adaptive logic behaviour from intersection-related conflicts to lane departure scenarios, thoroughly highlighting the logic capabilities in limiting the frequency of impacts and the injury consequences of vehicle-to-vehicle crashes.

Future work will be dedicated to the introduction of carriageway limits and obstacles in the software environment to limit the possible steering angle for the ego vehicle, which are currently unconsidered; the influence of the sensor field of view, the inertial properties, and the shape of the vehicles involved in the impacts will also be studied. The considered steering angles are limited and do not lead to driving instability; in the case of impact avoidance, specific interventions should be sought to make the ego vehicle regain its standard position on the lane once the opponent is far. At the moment, a comparison between the AEB and the adaptive logic has been performed, neglecting the activation time of the braking and steering systems: given the need to perform in-depth studies on the topic, the indications obtained in terms of the adaptive logic capabilities in such ideal conditions lay a solid basis for the continuation of the activities for the inclusion of the activation time in the software-in-the-loop routines. For instance, the logic in its current form can be ameliorated by including the possibility to account for the slope of the road, which translates into a constant force applied to the involved vehicles (concordant with the motion in the case of a downhill road and opposite in the case of uphill). Analogously, a reduced value of road-tyre friction (eventually caused by adverse weather or pavement discontinuities) can be considered in the simulations to be performed by the adaptive logic, limiting the maximum deceleration and steering angles that can be achieved by the X-by-wire circuits.

Although the possibility of introducing an on-board, real-time calculation system to identify the outcomes associated with each possible intervention on braking and steering still needs to be deepened, the study proposes a set of interesting results to develop new generation ADASs for the management of braking and steering degrees in any critical scenario, including inevitable collision states.

**Author Contributions:** Conceptualization, M.-S.G. and K.D.; Software, M.-S.G.; Validation, D.V.; Formal analysis, D.V. and K.D.; Data curation, M.-S.G.; Writing—original draft, M.-S.G.; Writing—review & editing, D.V. and K.D.; Visualization, M.-S.G.; Supervision, D.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Merah, A.; Hartani, K.; Draou, A. A New Shared Control for Lane Keeping and Road Departure Prevention. *Veh. Syst. Dyn.* **2016**, *54*, 86–101. [CrossRef]
2. Stubler, T.; Niegl, M.; Förster, M.; Pfeffer, P.E.; Abhishek, R. Development and model-based calibration of the lateral controllers "steer-by-angle" and "steer-by-torque" of a lane keeping assistance system. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2021**, *235*, 2136–2147. [CrossRef]
3. Yu, L.; Wang, R. Researches on Adaptive Cruise Control system: A state of the art review. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2022**, *236*, 211–240. [CrossRef]
4. Pan, C.; Huang, A.; Chen, L.; Cai, Y.; Chen, L.; Liang, J.; Zhou, W. A review of the development trend of adaptive cruise control for ecological driving. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2022**, *236*, 1931–1948. [CrossRef]
5. Wu, X.; Yan, L.; Li, H.; Su, C. Forward collision warning system using multi-modal trajectory prediction of the intelligent vehicle. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2022**. [CrossRef]
6. Sander, U.; Lubbe, N. Market Penetration of Intersection AEB: Characterizing Avoided and Residual Straight Crossing Path Accidents. *Accid. Anal. Prev.* **2018**, *115*, 178–188. [CrossRef]
7. Kaempchen, N.; Schiele, B.; Dietmayer, K. Situation Assessment of an Autonomous Emergency Brake for Arbitrary Vehicle-to-Vehicle Collision Scenarios. *IEEE Trans. Intell. Transp. Syst.* **2009**, *10*, 678–687. [CrossRef]
8. Jurewicz, C.; Sobhani, A.; Woolley, J.; Dutschke, J.; Corben, B. Exploration of Vehicle Impact Speed–Injury Severity Relationships for Application in Safer Road Design. *Transp. Res. Procedia* **2016**, *14*, 4247–4256. [CrossRef]
9. Vangi, D.; Gulino, M.S.; Fiorentino, A.; Virga, A. Crash momentum index and closing velocity as crash severity index. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2019**, *233*, 3318–3326. [CrossRef]

10. Gulino, M.S.; Gangi, L.D.; Sortino, A.; Vangi, D. Injury Risk Assessment Based on Pre-Crash Variables: The Role of Closing Velocity and Impact Eccentricity. *Accid. Anal. Prev.* **2021**, *150*, 105864. [CrossRef]
11. Vangi, D. *Vehicle Collision Dynamics: Analysis and Reconstruction*; Butterworth-Heinemann: Oxford, UK, 2020.
12. Sieber, M.; Siedersberger, K.H.; Siegel, A.; Farber, B. Automatic Emergency Steering with Distracted Drivers: Effects of Intervention Design. In Proceedings of the 2015 IEEE 18th International Conference on Intelligent Transportation Systems, Gran Canaria, Spain, 15–18 September 2015; IEEE: Gran Canaria, Spain, 2015; pp. 2040–2045. [CrossRef]
13. Li, D.; Zhang, J.; Xiao, B.; Tang, B.; Hu, Z. Vehicle crash mitigation strategy in unavoidable collision scenarios: Focusing on motion planning by considering a generalized crash severity model. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 581. [CrossRef]
14. Vangi, D.; Virga, A.; Gulino, M.S. Adaptive Intervention Logic for Automated Driving Systems Based on Injury Risk Minimization. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2020**, *234*, 2975–2987. [CrossRef]
15. Song, S.; Chen, W.; Liu, Q.; Hu, H.; Huang, T.; Zhu, Q. A novel deep learning network for accurate lane detection in low-light environments. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2022**, *236*, 424–438. [CrossRef]
16. Wang, B.C.; Liu, C.Z.; Zhang, L.T.; Wang, D.S. An Innovative multi-sensor data fusion method based on thrice deeply-fusion architecture for multi-object tracking. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2022**. [CrossRef]
17. Liu, Y.; Wang, J.; Li, Y.; Li, C.; Zhang, W. Lane-GAN: A Robust Lane Detection Network for Driver Assistance System in High Speed and Complex Road Conditions. *Micromachines* **2022**, *13*, 716. [CrossRef]
18. Benterki, A.; Boukhnifer, M.; Judalet, V.; Choubeila, M. Prediction of Surrounding Vehicles Lane Change Intention Using Machine Learning. In Proceedings of the 2019 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Metz, France, 18–21 September 2019; IEEE: Metz, France, 2019; pp. 839–843. [CrossRef]
19. Vangi, D.; Begani, F.; Gulino, M.S.; Spitzhüttl, F. A vehicle model for crash stage simulation. *IFAC-PapersOnLine* **2018**, *51*, 837–842. [CrossRef]
20. Vangi, D.; Begani, F.; Spitzhüttl, F.; Gulino, M.S. Vehicle Accident Reconstruction by a Reduced Order Impact Model. *Forensic Sci. Int.* **2019**, *298*, 426.e1–426.e11. [CrossRef] [PubMed]
21. Gao, L.; Xiong, L.; Xia, X.; Lu, Y.; Yu, Z.; Khajepour, A. Improved vehicle localization using on-board sensors and vehicle lateral velocity. *IEEE Sens. J.* **2022**, *22*, 6818–6831. [CrossRef]
22. Liu, W.; Xiong, L.; Xia, X.; Lu, Y.; Gao, L.; Song, S. Vision-aided intelligent vehicle sideslip angle estimation based on a dynamic model. *IET Intell. Transp. Syst.* **2020**, *14*, 1183–1189. [CrossRef]
23. Xia, X.; Hashemi, E.; Xiong, L.; Khajepour, A. Autonomous Vehicle Kinematics and Dynamics Synthesis for Sideslip Angle Estimation Based on Consensus Kalman Filter. *IEEE Trans. Control. Syst. Technol.* **2022**, *31*, 179–192. [CrossRef]
24. Xia, X.; Xiong, L.; Huang, Y.; Lu, Y.; Gao, L.; Xu, N.; Yu, Z. Estimation on IMU yaw misalignment by fusing information of automotive onboard sensors. *Mech. Syst. Signal Process.* **2022**, *162*, 107993. [CrossRef]
25. Xiong, L.; Xia, X.; Lu, Y.; Liu, W.; Gao, L.; Song, S.; Yu, Z. IMU-based automated vehicle body sideslip angle and attitude estimation aided by GNSS using parallel adaptive Kalman filters. *IEEE Trans. Veh. Technol.* **2020**, *69*, 10668–10680. [CrossRef]
26. Liu, W.; Xia, X.; Xiong, L.; Lu, Y.; Gao, L.; Yu, Z. Automated vehicle sideslip angle estimation considering signal measurement characteristic. *IEEE Sens. J.* **2021**, *21*, 21675–21687. [CrossRef]
27. Scanlon, J.M.; Kusano, K.D.; Gabler, H.C. Analysis of Driver Evasive Maneuvering Prior to Intersection Crashes Using Event Data Recorders. *Traffic Inj. Prev.* **2015**, *16*, S182–S189. [CrossRef] [PubMed]
28. Gulino, M.S.; Fiorentino, A.; Vangi, D. Prospective and Retrospective Performance Assessment of Advanced Driver Assistance Systems in Imminent Collision Scenarios: The CMI-Vr Approach. *Eur. Transp. Res. Rev.* **2022**, *14*, 3. [CrossRef]
29. Vangi, D.; Virga, A.; Conigliaro, M.; Steffan, H.; Tomasch, E. Adas-assisted driver behaviour in near missing car-pedestrian accidents. In *Autonomous Vehicle*; IntechOpen: London, UK, 2016; pp. 1–30.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.