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Review

Assessment of Road Vehicle Accident Approaches—A Review

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Abstract: Given the complexity of the crashes and the increasing interest in public policies related to the reduction in both accidents and fatalities from road crashes, the proposed review of the specialty literature may serve as a starting point for individuals interested in developing studies related to road vehicle accidents, reconstruction methodologies, assessment of vehicles crashworthiness, as well as evaluation of occupants' behavior in different collision scenarios. Therefore, the present paper aims to offer a comprehensive overview of the specialty literature approaches in terms of road vehicle accidents through an analysis of the reconstruction methods used in the cases of vehicle-to-vehicle or vehicle-to-object crashes, as well as ways in which the crashworthiness of road vehicles is assessed by specialized organizations or individual experts. The addressed topics were summarized from a range of European and global strategies in the field of transportation, reports, testing protocols, as well as scientific research papers published in international databases. The main purpose of the present paper is to serve as a foundational resource for researchers and practitioners seeking to contextualize their work within a global framework.

Keywords: road vehicle; accident reconstruction; crashworthiness; occupant behavior; crash test protocol

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1. Introduction

When it comes to road vehicles, the design processes, as well as vehicle functionalities, usually begin from the primary objective of ensuring road traffic safety, as one of the prevention mechanisms proposed by the World Health Organization (WHO). Annually, 1.9 million fatalities are registered worldwide as a direct consequence of road traffic accidents, costing approximately 3% of the Gross Domestic Product (GDP) of each country [1]. While in most countries the main victims of road accidents are represented as vulnerable road users such as pedestrians, cyclists, and motorcyclists [1], at the European level, most people at risk are represented by vehicles' occupants (45%), followed by pedestrians (18%), motorcyclists (16%), and cyclists (10%) [2]. In order to ensure both active and passive safety of road vehicles, it is crucial to understand the main factors that contribute to the occurrence of road traffic accidents, as well as the vehicles' and occupants' behavior in such situations. Given the still high occurrence of road traffic accidents, as well as fatalities as a direct result of these events, despite the international and European targets of halving the road deaths by 2030 globally [3], respectively, reducing fatalities to zero in European countries by 2050 [4]. In this regard, joint efforts from car and component manufacturers, policymakers, and other stakeholders are needed to implement measures fit for the purpose of reaching these ambitious targets. Moreover, collaborations between public authorities, manufacturers, and researchers are necessary to develop both passive and active safety systems that would eventually enable the implementation of high-level autonomous vehicles on a large scale.

In order to understand the circumstances of road traffic accidents, previous studies have focused on data collection and forecasting methods, analysis techniques, and contributing factors for various purposes. For example, the overview presented in [5] tackles crash prediction models, which are based on data regarding accident occurrence in different regions, fatalities resulting from these accidents, and contributing factors, in order to identify unsafe road sections and to estimate the effects of the implementation of safety measures in different areas. In addition, in [6] it is highlighted that traffic data such as infrastructure type, road geometry, and weather conditions can provide valuable insights for road vehicle accident predictions and, ultimately, make it possible to identify the necessary safety measures to be taken by policymakers and authorities for reducing collision occurrence. Moreover, factors contributing to human losses, especially in the case of vulnerable road users such as pedestrians [7], need to be always updated in order to efficiently increase road traffic safety.

The present review-type paper aims to contribute to the state-of-the-art database of road traffic accident approaches by offering an overview of practices in terms of crash tests conducted for new cars by specialized organizations, crashworthiness assessment methods used by researchers, and the current trends in using accident reconstruction means. The proposed topic arises from the interconnectivity between statistical data analyzed to gather information regarding the incidence of road events and fatalities that resulted from them, accident reconstruction techniques, and research approaches aimed at finally understanding the circumstances that lead to road events, as depicted in Figure 1.

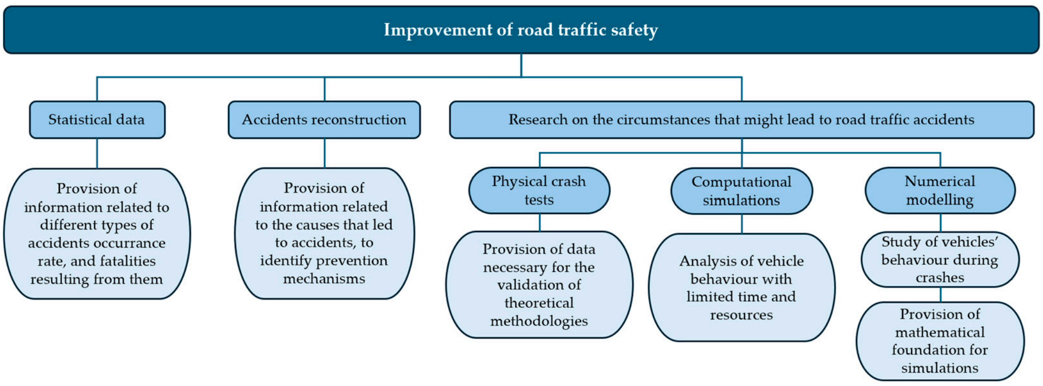

Figure 1. Interconnectivity between road vehicle accident analysis approaches and road traffic safety enhancement.

By synthesizing existing knowledge and identifying current trends, this review would provide a valuable resource for researchers involved in road safety. By analyzing crash test results and real-world accident data, weaknesses in vehicle design can be found to develop more effective safety features and improve occupant protection. The latter can also be improved by combining accident reconstruction data with biomechanical modeling and human factors research to improve injury prediction models. Moreover, insights from accident reconstruction can provide valuable information for policymakers when combined with statistical analysis of accident data so that informed road safety policies will be developed. In this regard, the paper addresses standardized international crash tests and identifies differences and similarities between geographical regions, then describes the findings from the specialty literature regarding a series of commonly used techniques for studying road vehicle accidents, namely computational simulations, use of video recording analysis and on-board data gathered from vehicles.

2. Standardized International Crash Tests

Standardized experimental testing for the crashworthiness of new cars, as well as the functionality of active and passive safety for both occupants and vulnerable road users, is realized by internationally recognized organizations based in different geographical regions. New cars are tested and assessed in terms of safety provided to road users and traffic participants, based on various road crash scenarios at different travel speeds, as summarized in Table 1. The diversity of test protocols is mainly given by the fact that those factors contributing to road vehicle accidents are grouped into four main categories: human, road, vehicle, and environment, and may vary from one country to another [8].

Table 1. Comparison between crash tests realized in the main geographical areas, based on collision type, travel speed, test particularities, and evaluated parameters [9–38].

Geographical Region (Organization)	Collision Type	Impact Velocity	Particularities	Main Evaluated Parameters
Europe (Euro NCAP)	Frontal collision with mobile, deformable barrier.	Tested vehicle: 50 km/h Barrier: 50 km/h	- Similarly to a collision between two vehicles, the second one being represented by the mobile deformable barrier of 1400 kg mass; - A 50% overlap on the driver's side.	- The degree of intrusion of the vehicle parts into the passenger compartment; - Forces and decelerations occurring to the head, neck, chest, and abdominal area of the driver, the front right occupant, and two child occupants in the back.
	Frontal collision with fixed, rigid barrier.	Tested vehicle: 50 km/h	- Full overlap of the vehicle's front part with the fixed, rigid barrier.	- Efficiency of restraint systems (seat belts) in protecting the driver and the passenger behind him.
	Lateral collision with mobile, deformable barrier.	Tested vehicle: 0 km/h Barrier: 60 km/h	- Similarly to a lateral collision between two vehicles, the barrier being collided with was the tested vehicle in the B-pillar area, on the driver's side.	- Protection offered to the driver and the two child occupants seated in the back.
	Far-side collision.	Tested vehicle: 0 km/h Barrier: 60 km/h	- The tested vehicle is hit on the opposite side to the driver.	- Efficiency of the central airbag mounted between the two front seats; - Movement of the occupant placed on the opposite side of the impact area, respectively, the injury risk.
	Lateral collision with a fixed, rigid pole-type obstacle.	Tested vehicle: 32 km/h	-	- Driver protection under the intrusion of the vehicle parts inside the passenger compartment.
	Rear-end collision.	Tested vehicle: 16 ÷ 24 km/h	-	- Whiplash effect on occupants, to evaluate the injury risk to the cervical spine; - Efficiency of passive safety systems aimed to protect the head and the spine.
	Frontal collision with pedestrian.	Tested vehicle: 40 km/h	-	- Risk injury to the head and lower limbs (basin, pelvis, knee ligaments).
USA (IIHS)	Frontal collision with fixed, deformable barrier.	Tested vehicle: 64 km/h	- A 40% overlap of the vehicle's front part on the driver's side.	- Protection offered to the driver and to a child occupant seated in the back, through the passenger compartment resistance structure and actuation of passive safety systems (seat belts, airbags).
			- A 25% overlap of the vehicle's front part on the driver's side. - A 25% overlap of the vehicle's front part on the front-right passenger side.	- Risk of injury to the lower limbs of the driver, respectively, the front-right passenger, as well as the occupant behind them.
	Lateral collision with mobile, deformable barrier.	Tested vehicle: 0 km/h Barrier: 60 km/h	- Mobile deformable barrier similar to an SUV that collided with the tested vehicle in the area of the B-pillar.	- Door deformations with respect to the remaining safety space in the passenger compartment for a female occupant.
	Rollover.	Static test	- A metallic plate impactor is used, which presses the vehicle's roof with a reduced and constant speed.	- Pressing force to which deformations of the vehicle's roof occur, until occupants are hit by the inside parts of the passenger compartment.
USA (NHTSA)	Frontal collision with fixed barrier.	Tested vehicle: 56 km/h	- Simulation of a collision between two vehicles having similar masses and dimensions.	- Passive safety offered to the vehicle's occupants.
	Lateral collision with mobile, deformable barrier.	Test vehicle: 0 km/h Barrier: 56 km/h	- The deformable barrier having a mass of 1367 kg is similar to a vehicle entering in a side collision with the tested vehicle.	- Risk injury to the occupants' head, neck, thorax, and pelvis.

Table 1. *Cont.*

Geographical Region (Organization)	Collision Type	Impact Velocity	Particularities	Main Evaluated Parameters
Japan (JNCAP)	Frontal collision with fixed, rigid barrier.	Tested vehicle: 55 km/h	- Full overlap of the vehicle's front part with the barrier.	- Driver's and front-right occupant's behavior.
	Frontal collision with fixed, deformable barrier.	Tested vehicle: 64 km/h	- 40% overlap of the vehicle's front part with the barrier; - Simulation of a frontal collision with a fixed, rigid obstacle at a speed of 55 km/h.	- Injury risk of the driver and the passenger behind him.
	Lateral collision with a mobile, deformable barrier.	Tested vehicle: 0 km/h Barrier: 55 km/h	- Simulation of a lateral collision between two vehicles, the second one being represented by the movable barrier having a mass of 1300 kg; - The impact takes place in the B-pillar area of the vehicle, on the opposite side to the driver.	- Injury risk for the vehicle's driver; - Efficiency of side curtain-type airbags.
	Frontal collision with pedestrian.	Impactor: 50 km/h	- Head- and leg-shaped impactors are used for both adult and child pedestrians; - The head-shaped impactor is projected to the vehicle's hood area.	- Head injury criterion; - Injury risk to the pedestrian's lower limbs.
Korea (KNCAP)	Frontal collision with fixed, rigid barrier.	Vehicle: 56 km/h	- Full overlap of the vehicle's front part.	- Driver and occupants' behavior; - Passive systems actuation time (seat belt restraint and airbag deployment).
	Frontal collision with fixed, deformable barrier.	Vehicle: 64 km/h.	- A 40% overlap of the vehicle's front part, on the driver's side.	
	Lateral collision with mobile, deformable barrier.	Vehicle: 0 km/h Barrier: 60 km/h	- Simulation of a lateral collision between two vehicles, the second one being represented by the mobile barrier having a mass of 1400 kg; - The impact is perpendicular to the B-pillar area of the vehicle.	- Injury risk for the occupants placed on the impact side and passive safety systems efficiency.
	Lateral collision with a fixed, rigid pole.	Vehicle: 32 km/h	- The tested vehicle is moved by a mobile platform; - The impact takes place in the B-pillar area, on the driver's side.	- Injury risk to the vehicle's driver and occupants.
	Frontal collision with pedestrian.	Vehicle: 40 km/h	- A head-shaped impactor is projected to the upper part of the vehicle's hood, respectively, to the windshield; - A leg-shaped impactor is hit to the vehicle's front bumper.	- Efficiency of passive safety systems aimed to reduce the injuries to the head and lower limbs of the pedestrian.
Latin America (Latin NCAP)	Frontal collision with fixed, deformable barrier.	Vehicle: 64 km/h	- A 40% overlap of the vehicle's front part with the barrier; - Simulation of a collision between two vehicles traveling with a speed of 55 km/h each and being overlapped by 50%.	- Injury risk of the driver, the passenger behind him, and two child occupants placed in the dedicated seats in the back.
	Lateral collision with mobile, deformable barrier.	Vehicle: 0 km/h Barrier: 50 km/h	- The impact occurs in the B-pillar area of the vehicle.	- Protection offered by the chassis and body structure to the vehicle's driver, the occupant behind him, and children placed in the back seat.
	Rear-end collision.	Sledge-type seat: low travel speed	-	- Efficiency of headrests in reducing injuries to the cervical spine.
	Frontal collision with pedestrian.	-	- A head-shaped impactor is projected to the vehicle's hood; - A leg-shaped impactor is projected to the vehicle's front bumper.	- Protection offered by the vehicle's body parts to the interest body areas of the pedestrian.
Australia and New Zealand (ANCAP)	Frontal collision with rigid barrier.	Vehicle: 50 km/h	-	-
	Frontal collision with mobile, deformable barrier.	Vehicle: 50 km/h Barrier: 50 km/h	- Simulation of a collision between two vehicles, the second one being represented by the mobile barrier having a mass of 1400 kg; - A 50% overlap of the front part of the vehicle, on the driver's side.	- Injury risk of the driver, the passenger in the back, and, respectively, a child occupant placed in the dedicated seat in the back.
	Lateral collision with mobile, deformable barrier.	Vehicle: 0 km/h Barrier: 60 km/h		- The intrusion of vehicle parts inside the passenger compartment; - Driver's and occupants' behavior.
	Lateral collision with a fixed, rigid pole.	Vehicle: 32 km/h	- Oblique orientation of the vehicle to the pole.	- The functionality of passive safety systems is aimed at protecting the head of the driver and the occupant behind him.
	Far-side collision.	Vehicle: 0 km/h Barrier: 60 km/h	- A mobile, deformable barrier is used; - The impact between the mobile barrier and the vehicle is on the opposite side to the driver.	- Injury risk of the driver's and front-right passenger's head; - Impact forces acting upon the neck and shoulders; - Protection offered by the seats and door trims; - Efficiency of seat belts in reducing injuries.
		Vehicle: 0 km/h Pole: 32 km/h	- A pole-type fixed, rigid obstacle is used to collide on the opposite side to the vehicle's driver.	
	Rear-end collision.	Reduced travel speed	- A sledge-type seat is moved along an inclined plane.	- Whiplash effect on risk injury to the cervical spine.
	Frontal collision with pedestrian.	Vehicle: 40 km/h	- The pedestrian's head is hit to the upper part of the vehicle's hood.	- Injury risk to the pedestrian's head.

2.1. Standardized Crash Tests in the European Region

At the European level, the European New Car Assessment Programme (Euro NCAP) aims to evaluate a vehicle's behavior in a series of collisions with other vehicles, fixed objects, and vulnerable road users, respectively. The expected outcomes are related to adults and children involved in these types of crashes. The frontal collision with another vehicle is simulated by using a mobile deformable barrier having a mass of 1400 kg and traveling with a speed of 50 km/h, the frontal crash being overlapped by 50% with the front part of the tested vehicle [9], thus representing the situation in which the tested vehicle would leave the travel direction and enter into a head-on crash with another vehicle coming from the opposite direction. The second case of frontal collision addressed by Euro NCAP captures the situation in which the tested vehicle travels at a speed of 50 km/h and collides with a fixed, rigid barrier, the frontal part of the vehicle being completely overlapped [10]. Regarding the assessment of occupant injury possibilities, in the first case, the anthropometric test device (ATD) used allows for the evaluation of the forces and decelerations occurring at the occupant's head, neck, chest, and abdominal area of the male driver, the male right-front occupant, and two child occupants in the back seat [9]. In the second case, the aim is to evaluate the restraint systems functionalities for a female driver and a female rear occupant by assessing how seat belts succeed in reducing the deceleration that occurs due to the structural rigidity of the vehicle [10].

Regarding side collisions, two main situations are addressed by Euro NCAP, namely the side collision between two vehicles using a movable deformable barrier and the side collision between a vehicle and a fixed pillar-type obstacle. In the first case, the tested vehicle is considered to be stationary and hit in the area of the B-pillar (between the two side doors) by another vehicle, using a mobile deformable barrier that is moved at a speed of 60 km/h, thus making it possible to assess the protection offered to a male driver and two child occupants seated in the rear [11]. The second situation, which, in practice, results from skidding or loss of transverse stability in cornering maneuvers, addresses the side impact between a projected vehicle at a speed of 32 km/h into a fixed, rigid pole of 254 mm diameter, aiming to evaluate the degree of protection for the driver's head, which can be hit inside the vehicle's cabin or by the pole itself when penetrating the side windows [12]. In addition, a third test situation in the case of side impact aims to evaluate the protection offered to the occupant on the opposite side of the impact area, by evaluating the functionality of safety systems, such as centrally positioned airbags with vertical openings, in limiting the movement of the occupant towards the area hit in the impact [13].

For front-rear collisions [14], of particular importance for the safety of adult occupants is the rapid movement with excessive distortion of the spine, a phenomenon called "whiplash", which is simulated in a low-speed impact of 16÷24 km/h. Thus, the action of the head and cervical spine restraint systems is assessed, with the aim of minimizing the risk of a movement that can cause irreversible diseases of the spine.

Considering the high European incidence of pedestrian deaths (18%) as a result of impact with a motor vehicle, especially in urban areas, generally at moderate travel speeds (40 km/h), the potential for pedestrian head injury is analyzed for both adult and child pedestrians [15]. Also, the potential of injuries in the upper leg area (basin and pelvis), and of the lower leg area (mainly injuries of knee ligaments), for adult pedestrians is analyzed, even though these do not present a risk of death but are often associated with long-term medical care [16].

2.2. Standardized Crash Tests in the United States of America

In the USA, the Insurance Institute for Highway Safety (IIHS) aims at testing motor vehicles, focusing on their resistance to different types of impact and, subsidiarily, the functionality of active safety devices designed to reduce the likelihood of road accident occurrence [17]. In the case of frontal collisions, it is aimed to test the vehicles colliding with a barrier-type obstacle, having different degrees of overlap of the frontal part of the vehicle, both in the driver's area (40% and 25%) and in the front passenger area (25%) [18]. In the case of a frontal impact between a motor vehicle and a deformable barrier, which simulates the collision between two vehicles usually occurring during overtaking maneuvers, the aim is to evaluate the degree of protection offered to the driver and the child passenger behind him through the construction of the passenger compartment and the actuation of safety belts and airbags at a travel speed of approximately 64 km/h [18]. The case of a vehicle collision with a rigid obstacle is carried out at a speed of 64 km/h with minimal overlap of the frontal part of the vehicle, allowing for the evaluation of driver protection in the case of a frontal collision with another vehicle or a fixed obstacle such as a tree or a pole. Given the reduced overlap, the contact surface is outside of the load-bearing structure of the vehicle, affecting the wheel assembly and the area of the passenger compartment intended to protect the lower limbs of the occupants [18].

On the other hand, the National Highway Traffic Safety Administration (NHTSA) approaches the frontal collision tests from the perspective of the impact between two vehicles of similar masses and dimensions, by hitting the testing vehicle with a travel speed of approximately 54 km/h against a fixed barrier [19].

In order to test new cars for side impact from the perspective of female occupant protection, the IIHS uses a movable deformable barrier, having the dimensions and mass of a sport utility vehicle (SUV), that collides with the tested vehicle at a speed of approximately 60 km/h in the B-pillar area, thereby causing deformation of the doors [20]. At the same time, NHTSA uses a mobile barrier with a mass of 1367 kg, which moves towards the lateral side of the stationary tested vehicle at a speed of 56 km/h, with the purpose of assessing the injury possibility of occupants' head, neck, chest, and pelvis [19].

In terms of rollover crashes, the IIHS tests the roof of the vehicle in order to assess the available space left for occupants inside the passenger compartment so that passive safety systems, such as curtain airbags and seat belts, remain effective [21]. The test takes place in static conditions, using an inclined metal plate that presses the vehicle's roof at a low but constant speed, aiming to determine the force at which it deforms until the occupants are hit by the inside of the cabin [21].

2.3. Standardized Crash Tests in Japan

Regarding the work of Japan NCAP, the evaluation of car safety provided to their occupants is conducted in the case of frontal collisions with full and 40% overlap, as well as side collisions [22]. The frontal collision test with full overlap involves the study of the driver's and front passenger's behavior in the event of a frontal impact with a fixed, rigid barrier, the tested vehicle traveling with a speed of 55 km/h. The 40% overlap frontal collision aims to assess the risk of injury to the driver and the passenger behind him in the event of a vehicle collision with a fixed, deformable barrier at a traveling speed of 64 km/h. According to the Japanese testing authority, the presented situation simulates the partial overlap in a frontal collision of the testing vehicle with a fixed, rigid obstacle at a speed of 55 km/h, similar to the previous test case [22].

The assessment of injury risk in the event of a side collision with another vehicle is carried out through an experimental test that involves the movement of a mobile, deformable barrier having a mass of 1300 kg at a speed of 55 km/h while the tested vehicle is stationary.

Thus, it is possible to evaluate the effectiveness of side curtain airbags in reducing the impact injuries caused to the vehicle's driver [22].

In terms of vulnerable road users' protection, JNCAP approaches this topic from the perspective of the assessment of the protection provided to the head and lower limbs of pedestrians in the event of a collision with a motor vehicle [23,24]. Thus, in the first test case, an impactor in the shape of the head of a child or adult pedestrian is used, projected towards the hood of the vehicle moving at an equivalent speed of 50 km/h, in order to evaluate the head injury criterion [23]. The second test involves the use of an impactor in the shape of the foot of an adult male pedestrian, hit by the front of the tested vehicle at a speed of 40 km/h, in order to assess the injuries occurring to the area of the knee and shin [24].

2.4. Standardized Crash Tests in Korea

Korean NCAP is responsible for conducting collision tests for motor vehicles in various scenarios. For example, the experimental testing of the frontal impact is carried out both with a rigid, fixed barrier, the tested vehicle moving at a speed of 56 km/h, and with a deformable barrier at a speed of 64 km/h, with 40% overlap on the driver's side [25].

The side impact is addressed, first of all, as a simulation of a perpendicular collision between two vehicles, by using a mobile, deformable barrier with a mass of 1400 kg, which is moved at a speed of 60 km/h, the impact with the tested stationary vehicle being made perpendicular to its B-pillar, on the driver's side [25]. Secondly, a collision between a vehicle moved by means of a mobile platform at a speed of 30 km/h is considered [25], the travel direction is inclined at a certain angle to the longitudinal axis of the vehicle, thus the occurring impact being with a fixed, rigid pole in the same area as the previous side crash test.

When it comes to vulnerable road users, KNCAP uses a pedestrian head-shaped impactor that hits the top of the hood and the windshield of the vehicle, as well as a foot-shaped impactor that hits the front bumper of a vehicle traveling at a speed of 40 km/h [25].

2.5. Standardized Crash Tests in Latin America

In South American countries, Latin NCAP tests vehicles in a frontal impact with a travel speed of 64 km/h, the collision occurring with a fixed, deformable barrier, with a 40% overlap on the driver's side [26]. Thus, it is possible to simulate a collision between two vehicles that would travel at 55 km/h, and the overlap of their frontal parts would be 50%. The aim is to assess the risk of injury to the driver and the front-right passenger, respectively, and to two child occupants located in the rear seats, in the dedicated restraints [26].

In the case of side impact, a mobile, deformable barrier is used, which moves with a speed of 50 km/h and collides with a stationary vehicle, the impact occurring in the area of the B-pillar of the vehicle, thus allowing the evaluation of the protection degree provided by the chassis and body structure, respectively, the deployment times of the side airbags for the driver, the occupant behind him, or the children placed in the dedicated seats in the back [27]. Another side collision considered is that of a vehicle moved with the help of a mobile platform at a speed of 39 km/h, which collides perpendicularly with a fixed, rigid pole-type obstacle, thus allowing the evaluation of injury risk for the head of the driver and the occupant behind him [28].

In order to evaluate the effect of whiplash in rear-end collisions between two vehicles, the ATD is placed in a seat as an integrated part of an experimental demonstrator, which is moved with a relatively reduced speed, thus assessing the effectiveness of head restraints in reducing injuries that may occur in the cervical spine area [29].

In terms of assessing vulnerable traffic participants' protection, the experimental testing consists of the use of impactors in the shape of the head, respectively, the leg of the pedestrian [30], similar to other standardized tests.

2.6. Standardized Crash Tests in Australia and New Zealand

In Australia and New Zealand, new car assessment is mainly focused on the protection of occupants in various collision situations, the protection of vulnerable road users, and the functionality of active safety features designed to prevent accidents from occurring.

The frontal impact of the vehicle with a rigid barrier is tested, with a vehicle travel speed of 50 km/h [31], thus evaluating the behavior of the driver and the occupant behind him. Also, in frontal impact, the aim is to simulate a collision with another vehicle by using a movable, deformable barrier having a mass of approximately 1400 kg, with which the tested vehicle collides with a 50% overlap of the front part on the driver's side at a speed of 50 km/h [32], aiming at the assessment of the injury risk for the driver, the rear passenger, and, respectively, a child occupant placed in the dedicated restraint seat.

Regarding the side impact with a fixed pole-type obstacle, the particularity of Australia NCAP testing consists of the fact that the tested vehicle is oriented oblique to the pole, unlike the previously mentioned tests where the pole is positioned perpendicular to the B-pillar of the vehicle. In this case, the speed of the tested vehicle is 32 km/h, and the functionality of the passive safety means is monitored from the perspective of protection to the head of the driver and the passenger behind him [33]. Another type of side impact is that of the vehicle crashing with a movable, deformable barrier, thus simulating the collision between two vehicles. In this situation, the mobile barrier has a mass of 1400 kg and travels at a speed of 60 km/h, being collided with by the tested vehicle on the driver's side [34]. One other category of side impact refers to the event of a collision between a vehicle and a mobile platform in the form of a deformable barrier having a travel speed of 60 km/h, respectively, a mobile platform in the form of a pole moved with a speed of 32 km/h, with which the tested vehicle enters into a side collision opposite to the driver's side, aiming to assess the risk of injuries to the head of the driver and the front passenger, respectively, the forces acting on their neck and shoulders [35], in relation to the protection provided by the seats and the inside of the door, respectively, the operation of the seat belts aimed to reduce injury severity.

For the evaluation of the whiplash effect, respectively, the risk of injury to the driver's cervical spine, the vehicle is tested in the event of a rear-end collision by using an inclined plane on which the ATD is placed in the seat of the vehicle under evaluation [36].

Pedestrians' safety is evaluated from the perspective of injury risk in the event of a collision in which the pedestrian's head hits the upper part of the hood of the tested vehicle, which travels with a speed of 40 km/h [37].

The overview of crash test protocols in different regions offers a wide picture of test approaches for new cars, aiming at providing information regarding road users' protection provided by the vehicle's passive systems in the selected cases by each organization.

For example, frontal collisions with mobile, deformable barriers, which simulate the real-case scenario of a frontal collision between two moving vehicles, are only addressed in Europe, and Australia and New Zealand, both the vehicle and the barrier moving with a speed of 50 km/h. In the USA, only IIHS addresses the collision between two vehicles by using a fixed mobile barrier. Similarly, the frontal collision between the tested vehicle and a stationary mobile barrier is evaluated in Japan, Korea, and Latin America, with the vehicle having the same travel speed of 64 km/h. In these cases, the travel velocity of the tested vehicle is higher due to the fact that a fixed barrier is used. Still in terms of frontal collisions, the ones with fixed, rigid barriers are present in Europe, the USA (by NHTSA), Japan, Korea, and Australia and New Zealand. The travel speed of the tested vehicle varies from 50 km/h (in Australia and New Zealand and Europe) to 55 km/h (in Japan) and 56 km/h (in the USA and Korea).

It is observed that all organisms, except Latin NCAP, address the full-width frontal collision with a fixed, rigid barrier at various travel velocities depending on the region (50 km/h in Europe and Australia and New Zealand, 55 km/h in Japan, and 56 km/h in the USA by NTHSA and Korea).

Lateral collisions with other vehicles are addressed by moving a deformable barrier to the tested new car, which is stationary, at a speed of 60 km/h (in Europe, USA by IIHS, and Korea), 56 km/h (in the USA by NTHSA), 55 km/h (in Japan), or 50 km/h (in Latin America). The impact between the barrier and the tested vehicle takes place in the B-pillar area, either on the driver's side (Europe) or on the opposite one, thus making it possible to evaluate both driver and front occupants' protection.

Even though lateral collisions with fixed objects such as poles occur as a secondary impact in most real-case scenarios, occupant protection is evaluated in this type of impact by Euro NCAP, KNCAP, and ANCAP at a speed of 32 km/h of the tested vehicle.

When evaluating the "whiplash" effect as a consequence of rear-end collisions, Euro NCAP tests the occupant protection provided by the vehicle's passive safety systems at a speed of 16÷24 km/h; Latin NCAP and ANCAP use a sledge-type seat at low travel speed, while the other new car assessment programs do not provide information about this particular test.

In terms of rollover collisions, it has been seen that in the USA, IIHS treats this evaluation as a static test by using an impactor pressing the vehicle's roof, while no details were found regarding the other organizations 'protocols.

Vulnerable road users protection is most of the time limited to vehicle-to-pedestrian standardized tests, aiming to evaluate the safety provided to the pedestrian's head and lower limbs (in the case of Europe, Japan, Korea, and Latin America) or only to the head in the case of Australia and New Zealand, at a relatively reduced vehicle travel speed.

When it comes to other mobility means, such as mopeds, scooters, and other micromobility vehicles, there are no test protocols in place, even though the use of these means has increased during the past years.

3. Computational Simulations Used in the Study of Road Vehicle Accidents

When it comes to evaluating the potential risks that a vehicle's occupants and other traffic participants are subject to in the event of a road collision, computational simulations are used due to their main advantage of reduced costs compared to destructive experimental tests presented in Chapter 2. The cost reduction comes from the repeatability of the simulating scenarios, as well as multiple iterations considered before the actual test of different collision scenarios and hypotheses.

A commonly spread method for assessing the crashworthiness of vehicles is one of finite element analysis. This method has proved a good accuracy of the results obtained through validation by comparison with experimental tests and the evolution of computing techniques that allow the processing of large series of data [38]. The finite element method aims to evaluate the pre-collision travel velocity of the vehicle, based on the deformations that occur both at those vehicle parts that absorb the largest amount of impact energy and at the level of the hit object [38]. In order to validate the finite element methods used, it is generally resorted to the comparison [38] of the results obtained and the calculation of the relative error between them through computer simulation software such as PC-Crash, which are based on the principles of classical mechanics for the determination of kinematic and dynamic quantities, taking into account the deformations that occur during the collision through the theory of momentum conservation [39,40]. In [39], the limitations of numerical modeling in the reconstruction of road traffic accidents are highlighted, given the nature of the classical mechanics used for this, which involves the determination of kinematic parameters that characterize the collision without analyzing how the deformations were produced. This is why, for a complex analysis of accident phenomena, it is proposed to supplement the classical methods with finite element analysis, which allows the correlation of kinetic energy losses during the impact with the deformations that occur at the level of the car body and resistance structure [39].

Also, the finite element modeling of different collision types aims to improve the load-bearing structure and the bodywork of vehicles from the perspective of the impact energy absorption capacity and the protection of both occupants and vulnerable road users. For example, ref. [41] presents the finite element modeling using the ANSYS software program for the case of a frontal impact of the behavior of longitudinal bars made of aluminum alloys, respectively, steel, located in the frontal area of the vehicle, having square or rectangular cross-sections. Thus, it is observed that the square-shaped cross-section leads to a 16% increase in the absorbed impact energy and a 15% increase in the maximum force to which it is subjected, compared to the rectangular section [39]. Regarding the material, the use of aluminum alloys leads to a 63% decrease in the vehicle's mass compared to steel, but, as a consequence, the energy absorbed during the impact is also reduced by 23%, respectively, the force to which the structure is subjected with 64% [41].

Given the complexity of accidents in which vehicle rollover occurs, in light of the longer time of the actual collision phase [42], respectively, the multitude of variables in the pre-collision phase and the uncertain trajectories of the vehicles in the post-collision phase, a more thorough analysis of the causes that lead to the occurrence of such phenomena, respectively, the behavior of the vehicle's occupants in such situations, is necessary. Therefore, in [42], an initial computer simulation is proposed with the help of the PC-Crash software program using accident databases, and the vehicle parameters thus determinedvelocities and accelerations, are being used afterwards in the finite element analysis for ensuring a higher accuracy of occupant behavior results.

With regard to road accidents caused by the improper operation of some driver assistance systems that equip vehicles, such as braking assistance, overtaking or lane-keeping assistance, adaptive speed control, parking assistance, pedestrian identification systems, or traffic sign recognition systems, automatic accident reconstruction algorithms are also proposed. These algorithms are based on a series of predefined collision scenarios, taking into account a series of parameters that characterize the functionality of these driver assistance systems [43]. Thus, the use of such an algorithm implemented with the help of the CarMaker software program developed by IPG Automotive contributes to the reconstruction of traffic accidents involving vehicles with a raised autonomy degree [43].

4. Video Recording Analysis in Road Accident Reconstruction

Due to the increase in the number of video cameras present for different purposes, such as surveillance and traffic monitoring, mounted in intersections, on buildings, or inside vehicles, it is possible to use the data from video recordings in order to reconstruct certain events, including road traffic accidents, through the possibility of correlating images with computer simulations for the evaluation of different dynamic and kinematic parameters [44]. Another use of video cameras is represented by detection purposes of vehicular accidents, by further image processing with machine learning algorithms such as those presented in [45]. The methodologies used to determine the relevant parameters in the study of road events depend on the type of video cameras with which the images were taken; fixed, mounted on poles or buildings, or mobile cameras mounted on the vehicle [46,47].

In [48] it is proposed to take the images recorded by the on-board video cameras positioned in the vehicles, to extract the trajectories of other vehicles captured in these recordings, and to introduce them into simulation algorithms for the automatic reconstruction of the movement scenario. The travel speed would be obtained by comparing successive frames capturing the targeted vehicle at different points on the tracked path, making the correlation with the technical specifications of the video equipment used. Even when using video cameras with low-quality images, such working methodology proved to be effective in the case of straight-line travel trajectories or slight turns on high-speed roads or highways, but less functional in the case of street intersections with low visibility [48]. Also, in [49], the pre-collision travel velocity of a studied vehicle is determined by tracking a point present throughout the video recording, based on the recording speed of the video camera. The study concluded that equipment having a recording speed of 120 frames/second is suitable for an accurate determination of the pre-collision speed.

If the environmental visibility is reduced while driving, for example, at night or due to weather conditions, in [50] the analysis of the acoustic signals taken from the audio-video recordings on board the vehicles is proposed. Thus, by isolating the frequencies and noises from the environment, the velocities of the targeted vehicles were obtained, with high accuracy in the case of traveling on a road with a noise-generating surface, either from irregularities or a noise strip equipping it [50].

5. Use of On-Board Data for Road Accidents Reconstruction

Event Data Recorders (EDRs) mounted on board vehicles have the role of storing information recorded in a short time interval of the order of seconds in the case of a road event. The recorded data refer to the dynamic behavior of the vehicle in the pre-collision phase, the driver's maneuvers in the pre- and actual collision phases, and, respectively, the activation of the passive safety systems (triggering the airbag and the seat belt) in the post-collision phase [51]. Equipping new vehicles with these data recording devices became mandatory in the period 2022–2024 for European vehicle manufacturers [52], thus contributing to road traffic safety from the data monitoring and tracking perspective.

The specialized literature approaches the topic of data recording devices on board the vehicle from the perspective of the possibilities to use stored information in order to improve traffic safety. The necessity to use the data provided by EDR appears mainly when the given collision case does not allow for the exact determination of the pre-collision velocities of the involved vehicles (for example, in the case of accidents in which skidding is followed by rollover, the case of oblique collisions under a certain angle of inclination in the vertical direction, or in the case of collisions with narrow objects) [53]. At the same time, the analysis of the information taken from EDRs offers the possibility of a statistical study of road traffic accidents from the perspective of vehicle drivers' reactions. For example, in [54], the maneuvers of the drivers in the moments preceding collisions in intersections are analyzed, using data taken from the EDRs. In this sense, 135 EDRs revealed the pressing of the brake pedal in the pre-collision phase, while the other 59 EDRs recorded data related to the vehicle's rotation. Thus, it was concluded that in 80% of the analyzed situations, the drivers performed collision avoidance maneuvers, such as braking and turning. The average braking time before impact was between 0.5 and 1.5 s, and the average reaction time to avoid the collision was between 0.5 and 0.9 s. Analysis of braking time showed that in 61.3% of cases, full braking occurred with the wheels locked or rolling, and those drivers braked less than the ones crossing the intersection without giving priority [54].

Another example is that of correlating the data collected from the EDR with police or forensic reports in order to establish the pre-collision behaviors of drivers and car passengers. Thus, the tendency to accelerate or decelerate the vehicle before the impact is observed, respectively, the rate of seat belt wearing and its correlation with the injuries that occurred in certain road accident cases considered [55].

6. Conclusions

In order to ensure and enhance road traffic safety, joint efforts of vehicle manufacturers, policymakers, authorities, and vehicle safety evaluation organizations are needed. Information exchange between these stakeholders enables data-driven and evidence-based policymaking, technical standards, as well as new road vehicle development for the safety of all traffic participants. Through continuous collaboration, reaching the European Union's desideratum of exempting road traffic fatalities by 2050 would be closer.

By understanding the various collision situations taken into account in different geographical regions, as well as the means of using the output data resulting from experimental crash tests, researchers and vehicle manufacturers have the possibility to work on the implementation of those measures aimed at increasing vehicle safety. However, it is worth noting that in order to achieve the proposed targets in terms of traffic safety enhancement, it is important to consider a wider range of vehicle collisions when designing new safety features.

At the same time, having a broad view of the computational simulation and information processing gathered before, during, or after a vehicular crash, it is possible to better understand the circumstances in which it was produced, thus contributing to the enhancement of active safety measures having the purpose of preventing traffic events. The choice of the implemented approaches in studying vehicle accident dynamics, either from the crashworthiness point of view or in terms of reconstruction, should be based on the available input parameters for each case study and the capabilities of the proposed methodology, as depicted in Figure 2, correlated with the provisioned outcomes.

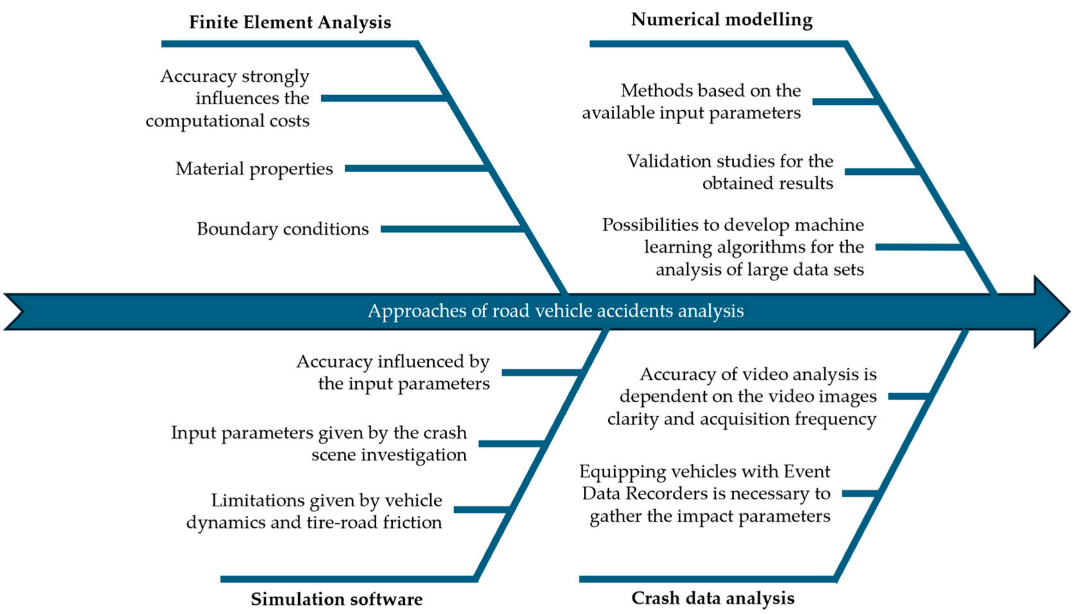

Figure 2. Summary of the approaches for studying road traffic accidents, given the main characteristics of proposed methodologies.

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