Post-Impact Stability Control for Road Vehicles: State-of-the-Art Methodologies and Perspectives

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***Abstract*— Reducing traffic accidents and associated casualties is a growing concern for modern human society. The secondary or even chain collisions for an unstable vehicle after an initial impact can result in more hazards and fatalities. Passive safety systems such as airbags and seat belts only provide limited level of protection for vehicle occupants, but cannot prevent collision accidents, while active safety systems usually work before the initial collision. Therefore, it is of great significance to develop dedicated post-impact stability control systems to help vehicles quickly restore stability to mitigate and/or avoid secondary collisions. However, the loss of original nonholonomic constraint property and the nonlinearity and saturation of tire forces due to post-impact sideslip, over-spinning, and drifting motions pose great challenges in controller design. Moreover, how to simulate and analyze the collision process and to further construct a simulation environment is the primary problem to solve for enabling controller development. Also, exploring repeatable, effective and low-cost experiment methods lays the foundation for controller verification. This paper aims to provide an overview of the latest technological advancements in collision modeling, control synthesis, and experimental procedures for post-impact stability control. The advantages and disadvantages of different modeling, control and experimental approaches are compared in succession. Finally, the paper discusses the challenges encountered in existing research and the prospects for post-impact active safety control systems.**

***Index Terms*— Collision modeling, active safety control system, vehicle dynamics control.**

I. Introduction

CAR ownership has seen continuous increase worldwide, providing people with increased travel convenience and contributing significantly to social and economic activities. However, the increasing number of road vehicles has also resulted in more traffic accidents, causing numerous casualties and significant property losses [1]. In the United States, for example, there were 5.42 million road vehicle crashes reported in 2010, resulting in 30,296 fatalities. These numbers rose to 6.76 million crashes and 36,096 deaths in 2019, according to the National Highway Traffic Safety Administration (NHTSA) [2]. Chain crashes were responsible for 30% of all fatal accidents, a number that is expected to further increase in the case of high-speed crashes [3]. Vehicles with high initial speeds tend to lose control more easily, even after a minor collision impact [4]. In contrast, vehicles with greater initial post-impact kinetic energy would experience more severe secondary accidents when they are out of control [5]. Additionally, rollovers and secondary lateral collisions can intrude directly into insufficiently protected passenger compartments, causing fatal injuries for passengers.

According to operation mode, the existing vehicle safety systems can be classified into two categories: active safety systems, such as Electronic Stability Control (ESC) [6], and passive safety systems, such as airbags [7]. The active safety system is typically activated prior to initial collision occurrence, and employs enabling control methods to intervene in vehicle motion via different actuators. The passive safety system is often triggered during collision accidents, and focuses on structural design to minimize bodily injuries. However, as shown in Fig. 1, ESC may fail in a typical secondary collision scenario as it functions near vehicle stability boundaries [8]. The additional yaw moment generated by differential longitudinal forces at four wheels is limited due to tire saturation caused by post-impact vehicle sideslip or drifting. As a result, safety protection from initial collision until the vehicle comes to a stop depends solely on passive safety systems [9]. Nevertheless, it cannot directly prevent secondary accidents and has limited protection effects. Therefore, the development of a specialized post-impact active safety system is of high significance. Cisneros analyzed different working intervals of various safety systems and proposed to pay as much attention to post-collision systems as to pre-collision ones. The design and verification processes should also satisfy the functional requirements of relative standards [10].

The abrupt changes in vehicle yaw rate and lateral velocity after a collision can cause the vehicle over-spin and drift severely. This presents significant challenges for the design of post-impact active safety systems. First, the vehicle's

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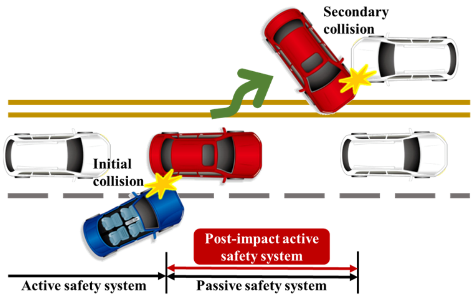

Fig. 1. A typical secondary collision scene.

kinematics loses its original nonholonomic constraints, and the tire forces become highly saturated, nonlinear, and mutually coupled [11]. Additionally, drivers may find it challenging to timely perform appropriate maneuvers in panic and fright [12]. After a collision, the average brake reaction time (BRT) increases from 0.5 seconds to 0.75-2 seconds [13]. Thus, post-impact active safety systems must not rely on the driver's control inputs. Lastly, the desired post-impact active safety system must achieve the balance between stability recovery and motion optimization, thereby addressing the complex multi-objective control problem under extreme post-impact conditions.

Based on the above analysis, it can be concluded that high-speed vehicles are susceptible to instability after a collision, making it challenging for the driver to regain control in a short period, and thus are more prone to secondary or chain collisions. Active safety control systems operate near the quasi-stable state before an accident, and passive safety systems cannot intervene in secondary collisions. In this context, post-impact active safety control systems are crucial in protecting vehicle safety and occupants after initial collisions. Moreover, multi-actuator coordination and motion optimization are the forefront research directions to enhance control effectiveness and prevent secondary collisions.

This paper summarizes and analyzes key technologies in post-impact active safety control from three aspects: vehicle collision modeling, post-impact control, and experimental procedure development. Vehicle collision modeling is the premise for post-impact controller development, as it provides an approach to describing the impact force, damage degree and post-impact motion. Also, it serves as a simulation environment for controller development. The review of post-impact control methods is the core while the overview on verification approaches presents how to test the controller performance repeatably and efficiently at low cost, and achieves the closed-loop design process for post-impact controllers. Furthermore, this paper discusses the challenges of current research and presents the prospects of vehicle post-impact active safety control systems.

The structure of this paper is organized as follows: Section II introduces the main vehicle collision modeling methods. Section III elaborates on the state-of-the-art post-impact active safety control methods. Section IV discusses various experiment methods for post-impact active safety control verification, followed by key conclusions and prospects summarized in Section V.

II. Vehicle Collision Modeling

Establishing a vehicle impact model in a collision accident is the premise for developing an effective post-impact active safety control system. Analyzing the impact process provides an assessment of the impact impulse and its damage degree, which lays the foundation for predicting the vehicle's motion and trajectory after collision. The existing vehicle collision modeling methods can be divided into three categories: finite element modeling, reduced-order dynamics modeling, and momentum conservation modeling methods. Table I summarizes and compares these three modeling approaches.

A. Finite Element Modelling Method

The Finite Element Method (FEM) divides the computational domain into finite and non-overlapping units based on the mechanics theory. This decomposition creates a discrete model composed of finite elements for solving field problems described by differential equations. Subsequently, numerical solutions can be obtained with computer assistance [14].

FEM has been widely applied to modelling vehicle collision and has shown good agreement with real experiments. The vehicle body is meshed using solid elements and mesh node attributes are assigned based on different materials used on the vehicle body. The deformation and mechanical changes of the vehicle during a collision can be calculated as a result. To aid in the establishment of 3D models and finite element analysis, various commercial software tools have been developed including LS-DYNA [15], [16], PAM-CRASH [17], [18], and ABAQUS [19]. These software tools are extensively used in optimization of vehicle structural strength and evaluation of crashworthiness [20]. For instance, Babu et al. from Daimler AG developed truck's body structure, interior parts, and dummy models using LS-DYNA. The interface component analysis method was used to calculate the variation in acceleration load at different points in the cockpit. This was achieved depending on the LS-DYNA's nonlinear solution capability and its applicability to both elastic and plastic materials. A study demonstrated that the LS-DYNA model was closer to the results of the full vehicle crash test compared to the sled vehicle simulation test [21]. Analogously, Duni et al. used ABAQUS to analyze the collision safety of the vehicle body structure in rollover accidents. However, it only allowed for quasi-static collision analysis in a single step. To simulate and analyze the entire collision process, the FEM analysis needs to be conducted at each step, which is time-consuming and computationally intensive [22]. Solanki et al. from Mississippi State University sought to confirm the versatility of various software tools by creating a vehicle model in both LS-DYNA and PAM-CRASH and comparing their simulation accuracies under the same conditions. The results indicated that both tools produced an error of 5-10% when compared to experimental data. However, PAM-CRASH demonstrated poor precision when simulating certain special materials such as honeycomb and foam [23].

FEM can provide accurate simulation of vehicle collision process. Benefitted from mesh generation flexibility, the occupant, seat and other in-cabin elements can also be modelled

TABLE I
TAXONOMY OF VEHICLE COLLISION MODELLING METHODS

Group No.	Classification	Advantages	Disadvantages	Application	No.	Model name	Representative references
1	Finite Element Modelling Method	High-precision simulation of vehicle collision and deformation	Huge calculation amount and complex material configuration. Restrictions on vehicle freedom	High-precision collision process and impact impulse magnitude analysis	1	LS-DYNA	[16] [24] [25]
					2	PAM-CRASH	[17] [18] [23]
					3	ABAQUS	[19] [22]
2	Reduced-order Dynamics Modeling Method	Better calculation efficiency and retains the key force and deformation characteristics	Dependence on the high-precision configuration or identification of model parameters	Vehicle collision dynamics, collision acceleration analysis	4	SMAC (EDSMAC, EDSMAC4)	[26] [27] [28]
					5	Node-based model	[29] [30]
					6	Lumped parameter model	[31] [32] [33]
3	Momentum Conservation Modeling Method	Rapid analysis of impact impulse of both forward and reverse process. Convenient combination with dynamics model	Relatively poor simulation accuracy and cannot reflect the vehicle deformation or force in detail	Accident scene reconstruction and liability analysis, vehicle collision dynamics and controller design	7	Crash algorithm (Crash 3, Crash PC, Smash, Winsmash)	[34] [35] [36]
					8	PC-Crash	[37] [38] [39]
					9	3 Dof model	[40] [41]
					10	4 Dof model	[42] [43]
					11	Iterative momentum conservation model	[44] [45] [46]

in the collision process. For example, Kitagawa et al. utilized LS-DYNA to analyze the influence of seating position, direction and angle on occupant kinematics [24], while Jin et al. combined the LS-DYNA and human body finite element model THUMS to study the occupant kinematics and biomechanics with rotatable seats [25].

However, FEM requires the pre-configuration of grid areas with different properties based on the parts and material characteristics, which can result in many grid areas. Additionally, due to the stringent computational requirements of FEM, high-performance computing resources are necessitated. Moreover, FEM also restricts some Degrees-of-Freedom (DOFs) of vehicle to determine the boundary conditions, which limits the ability to fully reflect vehicle dynamics and motions. Therefore, FEM-based numerical modeling is more suitable for analyzing the collision process and determining the impact impulse magnitude for active safety controller design.

B. Reduced-Order Dynamics Modeling Method

Various reduced-order dynamics modeling methods have been proposed to improve the computational efficiency of collision modeling while accounting for changes in vehicle dynamics and kinematics. These methods simplify the complex mass distribution and deformation characteristics of vehicle by demensionality reduction. Specifically, they abandon less influential degrees of freedom and only retain critical collision characteristics. Reduced-order dynamics models can be classified into two categories according to the used dimensionality reduction methods: interface stiffness models and lumped parameter models. The interface stiffness model reduces body deformation to a two-dimensional plane, while the lumped parameter model reduces the vehicle body mass distribution to a lumped mass unit.

Simulation Model of Automobile Collisions (SMAC) is a popular interface stiffness model that was first proposed by McHenry from the Calspan Crash Test Laboratory, with

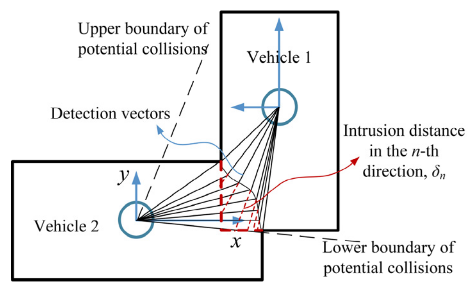

Fig. 2. Collision detection and calculation model in SMAC.

support from NHTSA [47]. SMAC combines vehicle dynamics with the Hooke's Law and consists of a collision calculation module, a vehicle dynamics module, and a motion prediction module. At each time step, the collision calculation module detects a possible collision angle range and generates multiple detection vectors based on a small angle interval within the range, as shown in Fig. 2. The intrusion distance in the n-th vector direction, $\boldsymbol{\delta}_n$, is then determined by analyzing the vehicle's contour lines and their actual relative locations. The local collision force, $\boldsymbol{F}_n$, caused by collision deformation can then be calculated using the Hooke's law by

$$\boldsymbol{F}_n = K_v \boldsymbol{\delta}_n \tag{1}$$

where K_v is the body stiffness. The overall collision force is determined by summing the vector collision forces within the potential collision angle range. The vehicle dynamics module then uses a built-in 3-DOF model (longitudinal, lateral, and yaw) to calculate the tire sideslip angle and force for each tire. Finally, the motion prediction module integrates accelerations based on the tire and collision forces to determine speed and location changes [48]. By doing so, the vehicle's motion trajectory throughout the entire collision process can be obtained.

The development of SMAC has enabled NHTSA to analyze thousands of traffic accidents. Initially, SMAC was packaged as a batch mode program for deployment on mainframe computers. A version called EDSMAC, designed for personal computing platforms, was subsequently developed by the Engineering Dynamics Company [49]. EDSMAC retained the basic algorithm structure of SMAC while adding in a user interaction interface. To improve simulation accuracy for low-speed collision accidents, EDSMAC4 was developed [26], and the stiffness characteristics described in Equation (1) were modified as

$$\boldsymbol{F}_n = A_n + B_n \boldsymbol{\delta}_n \tag{2}$$

where A_n and B_n are the critical deformation stress value used to correct the contact stress in the initial collision stage and the elastic stiffness in the n-th vector direction, respectively [50]. EDSMAC4 includes a load transfer calculation module and supports the analysis of special collision scenarios such as flat tires and articulated vehicles. A comparative study conducted in [51] demonstrates that EDSMAC4 has superior accuracy and adaptability to multiple scenarios when compared to its older versions. Taking EDSMAC4 as the kernel, some commercial software with visual interface have been widely used to reconstruct collision scenes, such as HVE from the Engineering Dynamics Company. For example, Eichaker utilized HVE to analyze how difference in cargo loading affects crash kinematics [27]. Scanlon et al. successfully reconstructed collision scenes by ingesting the kinematics data from HVE into the Waymo's simulation environment [28].

Similarly, Vangi et al. proposed a reduced-order dynamics model based on evenly-distributed nodes along the vehicle's outer contour [29]. This node-based model forms an effective envelope of the collision contact boundary of the vehicle body [30]. Elastic stiffness characteristics are configured near each node, and the collision contact stress at each node is calculated at each time step based on node displacement. The vehicle motion is deduced further based on the vehicle dynamics model.

The reduced-order dynamics models, based on vector distribution and node distribution, have combined finite element theory and vehicle dynamics to achieve high-precision prediction of microscopic impact force and macroscopic vehicle motion. However, the computational efficiency and modeling accuracy still largely depend on the division of detection units. To address this issue, related research proposed a lumped parameter collision model that abstracts the components with similar characteristics in the body structure into multiple masses and elastic elements, thereby reducing the dimensions of the collision problem. For instance, Pahlavani et al. proposed a 12-DOF lumped parameter model [31]. The model employs multiple mass units to represent various components such as engine, bumper, and other interconnected parts, which are connected using multiple elastic and damping units. Similarly, Elkady et al. modeled the 6-DOF vehicle crash dynamics and multi-body occupants together with lumped masses, nonlinear springs and dampers. [32]. Meanwhile, Jonsén et al. developed a lumped parameter model that uses single-dimension and multi-mass units connected in series, as shown in Fig. 3. This model can further enhance computational efficiency; however, it is only suitable for frontal collision scenarios due to its single-dimension characteristic [33].

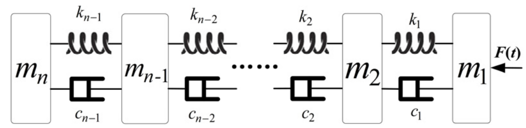

Fig. 3. One-dimensional mass spring damper model.

The reduced-order dynamics model based on the lumped parameter method can not only ensure computational efficiency but also retain the essential deformation characteristics of the vehicle body. Additionally, it provides information on the acceleration loads of key units inside the vehicle body. However, this method is dependent on high-precision configuration or identification of the lumped parameters for each unit.

C. The Momentum Conservation Modeling Method

The momentum conservation modeling method analyzes the collision process by taking the vehicle as a whole, and focuses on simulating the vehicle's behaviors during collisions to quickly and accurately reproduce its dynamics changes. By combining the conservation of momentum and impulse with the Hooke's law, researchers have developed various multi-DOF vehicle models for collision simulation. While the reduced-order dynamics modeling method can precisely recreate the collision process, it requires accurately knowing the initial speed and is unable to perform reverse analysis based on post-collision states. In contrast, the momentum conservation modeling method can analyze both forward and reverse collision processes by examining the state changes before and after collision.

The CRASH algorithm was developed by the Calspan laboratory to realize traffic accident reconstruction and liability determination in the cases where initial speeds are unknown. The algorithm is based on the principle of conservation of momentum and energy [34] and serves two main purposes. First, it is used to assist the SMAC algorithm in estimating the initial speed. Secondly, it is used by NHTSA for rapid accident data classification and statistical analysis as it can quickly approximate the speed change (Delta-V) before and after collision, which is an important criterion for evaluating the degree of collision hazards [52]. The CRASH algorithm has undergone several modifications, resulting in different versions such as CRASH3 for large-scale hosts, CRASH PC for DOS, and SMASH for WINDOWS. Volpe National Transportation Systems Center integrated a more user-friendly interface and the NHTSA traffic accident database into SMASH to create WinSMASH [35].

The CRASH simulation models consist of two sets of analysis algorithms: the trajectory and the damage analysis algorithm. The trajectory analysis algorithm determines the separation speed of the collision vehicles by analyzing the vehicles' end positions, tire trajectories, and road adhesion coefficient [53]. The vehicles' approaching collision speed and Delta-V are then calculated based on the conservation of momentum and angular momentum, making the trajectory analysis algorithm more suitable for being used in offset collision scenarios. The damage analysis algorithm establishes an approximate linear stiffness function for the absorbed energy (E_A) due to vehicle body deformation and crushing depth (C) as

$$\sqrt{\frac{2E_A}{w}} = d_0 + d_1 \times C \quad (3)$$

where w is the width of the body crushing area, while d_0 and d_1 are the intercept and slope to describe the linear elastic model [54]. Considering the discrepant crushing depths for different parts, Equation (3) is modified as the integral of deformation absorbed energy within the crushing area as

$$E_A = \int_0^w \frac{1}{2} \times (d_0 + d_1 \times C(w))^2 \, dw \quad (4)$$

The energy absorbed by the vehicle body deformation can be calculated using the stiffness function based on the measured crush. Using the conservation of momentum and energy, the speed change during the collision process can then be obtained. The calculation process relies on an approximate momentum conservation and a linearized energy-deformation model, with the stiffness coefficient being a crucial parameter. However, the stiffness coefficient is sensitive to several factors, including vehicle type, invasion position, and collision angle, and this may lead to complex anisotropy. Several stiffness coefficient identification methods have been proposed in the literature. For example, Brach et al. presented a theoretical calculation method for determining the stiffness coefficient in laboratory environments [36]. This method involves testing the critical speed without obvious crushing deformation in a light collision and then calculating the intercept d_0. The mean value of d_1 is further obtained based on the kinetic energy calculated using the initial speed and the crash deformation in multiple violent collisions. Moreover, Struble et al. modified the energy calculation method to improve stiffness coefficient identification accuracy [50]. The modified method considers the energy loss in an inelastic collision and introduces the recovery coefficient e in the momentum conservation as

$$V_{2n} - V_{1n} = -e(v_{2n} - v_{1n}) \quad (5)$$

where V_{1n} and V_{2n} are the instantaneous speed components of the two vehicles in the normal direction of contact surface after collision; v_{1n} and v_{2n} are the ones before collision. However, the determination of e is empirical. Karapetkov et al. proposed a mathematical modelling method based on the dynamics model of two-vehicle collision, which eliminates the need to select an appropriate recovery coefficient by solving the Cauchy problem [55]. Additionally, Vangi et al. utilized cameras and motion sensors to capture the dynamic crush deformation [56]. This reduced the measurement error caused by deformation recovery and improved the accuracy of stiffness coefficient identification. Nevertheless, this method involves a complicated experimental procedure and may fail to produce universal results. Alternatively, Nathan et al. classified a large amount of collision data from the same vehicle under similar collision scenarios and identified the vehicle body's stiffness coefficient using a linear regression method [57]. The data analysis approach provides a simpler and more accessible method for determining the stiffness coefficient compared to the experimental method.

Hermann et al. developed the PC-Crash algorithm to model the dynamics and kinematics changes of vehicle with high accuracy after they encounter impacts [37]. PC-Crash uses complex vehicle dynamics models, including tire, suspension, and aerodynamic models, to simulate vehicle post-impact motion with high precision [58]. The vehicle speed change at the instant of collision is calculated according to the conservation of momentum and angular momentum, and the recovery coefficient characterizes the kinetic energy loss in an inelastic collision [59]. Rose et al. compared PC-Crash and other simulation programs and demonstrated that vehicle dynamics can effectually contribute to improving simulation accuracy [38]. Moreover, Cliff et al. compared PC-Crash with full vehicle experimental data under various collision intensities and verified its high accuracy in predicting vehicle post-impact motion [60]. Additionally, PC-Crash supports the addition of vehicle control signals during vehicle dynamics calculation, including front-wheel steering angle, engine's output propulsion force, and four wheels' braking forces, which provides the foundation for vehicle dynamics control verification under collision scenarios [61]. For example, Daniel et al. compared the effectiveness of traditional ESCs and a dedicated post-impact stability controller by employing a PC-Crash control interface [39].

Likewise, Brach et al. simplified vehicle dynamics into a 3-DOF model to investigate the slight collision process. The conservation of momentum and impulse theorem was also utilized to avoid calculating the vehicle's local deformation and contact stress [40], [62]. The 3-DOF momentum conservation model was also utilized to reconstruct side collisions [41]. Furthermore, Zhou et al. expanded the 3-DOF vehicle model to a 4-DOF vehicle model by further including the roll motion [42]. To address the deficiency in the PC-Crash model, Zhou developed a piecewise linear lateral tire model and added tire lateral force impulse into the impulse theorem application for vehicle motion prediction. Moreover, the tangential friction coefficient along the collision contact interface is considered and is given by

$$\mu = \frac{P_t}{P_n} \quad (6)$$

where P_t and P_n are the tangential friction and normal impacts on the contact interface as shown in Fig. 4. Taking the high-fidelity vehicle dynamics model from Carsim as the reference, the modified 4-DOF collision model exhibits higher accuracy. Zhou et al. also used the collision model to analyze the typical scene of the Precision Immobilization Technique (PIT) [63]. PIT is a specialized approach that uses deliberate impact to destabilize and stop the target vehicle by striking its rear. By using the collision model in an offline simulation environment, critical factors that impact PIT efficacy are identified.

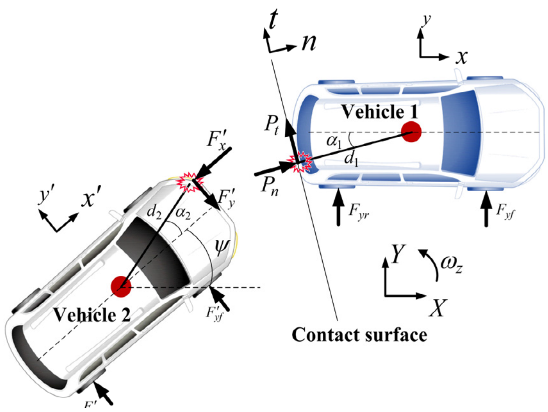

Fig. 4. Collision interface and collision impulse model.

The momentum conservation-based vehicle collision models require knowing initial vehicle states, impact duration, impact angle, and position of the impact center. They can only be used for offline simulation and analysis. In online applications, it is difficult to obtain the real-time collision process information. To ensure effective and timely intervention, a rapid modeling approach is required to provide necessary information before the collision is completely over. To tackle this issue, Kim et al. developed an iterative momentum conservation model that predicts post-impact motion at the early stage of collision [44]. This model estimates the longitudinal and lateral collision impulses and the impact point position during the initial 2-3 time steps of the collision process. The changing trend of collision force is then represented as an isosceles triangle contour based on the analysis of relevant experimental data [45]. These estimates are used to predict vehicle motion in real-time using a 4-DOF collision model. Wach et al. developed an impulse-momentum collision model for two vehicles in terms of planar mechanics [64]. While this model is relatively sensitive to the impact point position, it achieves a balance between computational efficiency and accuracy for accident simulation. Similarly, Germane decomposed the collision process into multiple phases, fitted the collision impulse to a rectangular contour, and applied the momentum conservation iteratively [46]. Based on the real collision data collected from NHTSA, it was shown that the simulation accuracy of the iterative modeling method is higher than the single-step modeling method under offset collision conditions.

In summary, the finite element modeling method can provide an accurate approach to observing the evolution of impact force during collisions. However, its integration with vehicle dynamics is limited due to high computational cost and complex boundary constraints. By retaining essential deformation characteristics and improving computational efficiency, the reduced-order dynamics modeling method shows better performance. While the momentum conservation-based collision modeling method can concisely describe the collision interaction, it suffers from poor accuracy. Therefore, an integration of the reduced-order dynamics modeling and iterative momentum conservation is promising for being used in post-impact control. Additionally, loading the derived impact impulses into a specialized vehicle dynamics simulation software, such as Carsim, CarMaker, and VeDYNA, allows for the analysis of post-impact safety control systems under various collision scenarios.

III. Post-Impact Active Safety Control

To restore stability to a vehicle after an initial collision, and to prevent or reduce injuries resulting from secondary collisions, various post-impact active safety control systems have been developed. These systems can be categorized into two main types: post-impact stability control based on a single actuator and multi-objective coordinated control based on multiple actuators. Table II summarizes the classification, advantages, limitations, control objectives, controller and actuator configuration for commonly used post-impact active safety control methods.

A. Post-Impact Stability Control Based on A Single Actuator

The control for traditional manned vehicles mainly involves with controlling the longitudinal force via the driving/braking system and the front-wheel steering angle via the steering system. Similarly, for automated vehicles or the vehicles with Advanced Driver Assistant Systems, extensive research has focused on post-impact active braking control and post-impact active steering control, commonly known as post-impact stability control based on a single actuator. Simple design and easy implementation make it widely used in production automobiles.

1) Post-Impact Active Braking Control: The mass adoption of the Anti-lock Braking System (ABS) has facilitated the development of post-impact active braking control. Fuerbeth et al. revealed that the post-collision run-out motion can be effectively attenuated through appropriate deceleration [65]. BOSCH developed the Second Collision Mitigation (SCM) system to determine the ideal intervention time using the collision trigger signal of an acceleration sensor integrated into the airbag [66]. Upon detecting a collision, SCM sends an emergency braking command to ABS to dissipate the vehicle's kinetic energy, thus alleviating the potential risks of secondary collisions. In 2012, Audi equipped its A3 model with the first mass-production Secondary Collision Brake Assist (SCBA), which can automatically deal with maloperation instructions resulting from driver's panic and assist in braking execution after a collision [44]. Furthermore, Skoda and Daimler have also developed similar post-impact active braking systems. According to statistics from the European New Car Assessment Program, vehicles equipped with post-impact active braking can help prevent 8% of fatal accidents and 4% of serious accidents, demonstrating its effectiveness in mitigating secondary collision hazards [67].

The braking intensity design is integral to developing an efficient post-impact active braking control system. Overly intense braking may destabilize the vehicle after high-speed collisions, while insufficient braking curtails the ability to avoid secondary collisions, particularly when the preceding vehicle is stationary or at low speeds. By analyzing the NHTSA's traffic accident data, most manufacturers have

TABLE II
TAXONOMY OF POST-IMPACT ACTIVE SAFETY CONTROL METHODS

Classification	Advantages	Disadvantages	Control objectives	Controller	Control actuators	References
Post-impact active braking control	Simple to design and implement. Low actuator configuration requirements.	Only applicable for central collision. Improper violent braking control may even worsen lateral stability.	Dissipate vehicle post-impact kinetic energy	Constant braking intensity	Global braking	[66] [67]
				Adaptive braking intensity	Global braking	[68]
Post-impact active steering control	Able to utilize tire lateral force for resuming lateral stability. Moderate design complexity and low computational cost.	Only effective under slight collision condition. Cannot deal with high-intensity collision when tire forces are saturated.	Lateral displacement and yaw angle error relative to the path	Forward preview control	Front steering	[70] [71] [72]
				Forward preview control + MPC	Front steering	[73]
Multiple actuators coordination control for system stability	Can achieve better stability recovery performance and the coordination of multiple stability targets with the help of multiple actuators even after high-intensity collision.	Relatively high complexity and computational cost. Only considers the stability recovery while the safety of secondary collision protection is not optimized directly.	Lateral speed and yaw rate	Double sliding mode control	Front steering + differential braking	[74]
			Lateral speed, yaw rate, and roll angle	MPC + optimal allocator	Front steering + differential braking	[43]
			Yaw rate and yaw angle	Linear sliding mode control + optimal allocator	Front steering + distributed driving	[75]
			Resistance yaw moment maximization	Offline optimal allocator	Front steering + differential braking	[76]
Multiple actuators coordination control for environmental safety	Benefiting from multiple actuators, the objectives of stability recovery and secondary collision protection are unified together by optimizing the post-impact trajectory and posture. Can improve the post-impact safety for a wide range of working conditions.	High design complexity and computational cost. Can only reduce the probability or hazard of a secondary collision, while cannot achieve the secondary obstacle avoidance effectively for a specific environment.	Yaw angle and lateral displacement	Fuzzy self-tuning PID control	Front steering + differential braking	[77]
			Yaw angle and lateral displacement	Neural network control based on RL	Front steering + front driving + rear differential braking	[78] [79]
			Yaw angle and lateral displacement	Sliding mode control	Front steering + differential braking	[80] [81] [82]
			Yaw angle and lateral displacement	Feed-forward control and LQR/MPC	Front steering + differential braking	[83] [84]
			Lateral displacement / Terminal global velocities minimization	Open-loop optimal control based on SQP	Front steering + differential braking	[85] [86]
			Lateral displacement minimization	Quasi-linear optimal controller	Front steering + differential braking	[87] [88] [89] [90] [91]
			Lateral displacement and safety terminal yaw angle	LTV-MPC + optimal allocator	Differential braking	[92] [4]
			Yaw angle and lateral displacement	LQR + PID	Front steering + partial differential braking	[93]
			Obstacle avoidance	Artificial potential field planning + LTV-MPC/TVLQR	Distributed driving	[94] [95]

defined an deceleration of 5.88 m/s^2 (0.6 g) as the optimal braking strength for active braking systems [68]. When using this braking strength, 50% of secondary collisions can be effectively avoided.

To enhance the system's efficacy under various driving conditions, Shotaro et al. created an adaptive brake intensity adjustment strategy for a post-impact active braking system [68]. It can adjust the braking intensity through a piecewise linear function according to post-impact vehicle speed. When operating at low speeds, full-load braking (1 g) is applied to reduce the braking distance while a mild braking as low as 0.5 g is preferred at high speeds, with linear interpolation applied at moderate speeds. Carsim simulation validated its efficacy in multiple driving scenarios, demonstrating its capacity to optimize braking intensity.

Although the active braking system can significantly reduce potential hazards of secondary collisions by dissipating kinetic energy, it has no control over the vehicle's motion [69]. It plays a significant role in central collision scenarios like rear-end collisions; but its performance would be severely compromised in sudden yaw rate and sideslip angle scenarios after lateral offset collisions. Besides, the tire force saturation caused by violent longitudinal braking may exacerbate the vehicle's unstable motion, increasing the risk of further collisions.

2) Post-Impact Active Steering Control: Active front steering control corrects the vehicle's heading angle and trajectory by generating a desirable yaw moment through tire lateral forces. Some studies have been carried out to modify the traditional active steering control system to explore its safety control potential in post-impact instability scenarios. For instance, Chan et al. proposed a closed-loop front steering controller based on the forward preview control theory to stabilize a post-impact vehicle [70]. The presented method adopts a tire model with an equivalent cornering stiffness and a simplified vehicle dynamics model. The system's state variables are the lateral displacement deviation ΔY and the yaw angle deviation $\Delta\psi$ from the reference trajectory after an initial collision. The feedback law is derived as

$$U = -G(\Delta Y + L \times \Delta\psi) \tag{7}$$

where U, G, and L are the front-wheel steering angle, feedback gain, and forward preview distance of the preview feedback controller. Tan et al. further determined the optimal controller gain and preview distance parameters by offline analyzing the zero-pole distribution of the closed-loop linear system [71]. Chan et al. further tested the active front steering controller's performance in multiple collision scenarios featuring straight and curved roads via SMAC [96]. Their findings reveal that the developed controller can restore the vehicle's trajectory tracking ability after external impacts and demonstrates robustness against vehicle parameter uncertainties.

To reduce the steady-state error inherent with preview feedback controllers, Chan et al. proposed to add in a steady-state gain compensator $C(s)$ [72]. The formulations of the proposed controller are given by

$$\begin{aligned} U &= -G(C(s)\Delta Y + L \times \Delta\psi) \\ C(s) &= \frac{s + 2\pi f_1}{s + 2\pi f_2} \end{aligned} \tag{8}$$

where s is the Laplacian operator; f_1 and f_2 are the frequencies set by offline calibration. The added compensator can amplify the low-frequency gain and improve the tracking accuracy in steady states without changing the controller's structure. Cao et al. integrated the Model Predictive Controller (MPC) with a forward preview feedback controller to achieve this purpose while using the output of the forward feedback controller as the initial control value of MPC for fast solution derivation [73]. Simulation results showed that the integrated controller could quickly intervene and restrain the vehicle's yaw and sideslip movements in early stages. However, this active steering control system can only address vehicle instability after slight collisions and provide limited ability to regulate vehicle motion and yaw stability in high-intensity collisions, especially when the front and rear tires enter their nonlinear regions.

B. Multi-Objective Coordinated Control Based on Multiple Actuators

The post-collision stability control system with a single actuator has limited control degrees of freedom while vehicle dynamics exhibiting strong nonlinearity with highly-coupled motion states in different directions. The independent braking control at each wheel provides the hardware foundation for developing a post-impact stability control system with multiple actuators [32], [97]. Depending on different control objectives, multi-actuator coordination controllers can be categorized into that for system stability and that for environmental safety [39].

1) Multiple Actuators Coordination Control for System Stability: Accurately detecting incoming collision events is a prerequisite for timely activating stability control systems. Zhou et al. employed the yaw rate and lateral acceleration as the characteristic states for triggering the control system after detecting threshold transgressions in three consecutive time instants [43]. A secondary collision confirmation mechanism was also designed to avoid false triggering, which predicts the vehicle state based on impact impulse estimation.

Based on the trigger mechanism, Zhou developed a post-impact stability sliding mode controller [74] utilizing a two-track planar dynamics model, double sliding surfaces, and exponential reaching law to derive the expected front-wheel steering angle and yaw moment generated by differential braking. The controller also included a rule-based braking force allocator and another linear sliding surface to track the expected slip rate.

Post-collision rollover can also be mitigated by an enabling post-impact roll stability controller. On this regard, Zhou established a roll-yaw linear dynamics model and designed a hierarchical post-impact stability control architecture that employed MPC at the upper layer and an optimal braking force distribution controller at the lower layer. The partial derivative of the Magic tire formula was used to linearize the optimal control problem, and Carsim simulation results verified the architecture's effectiveness in extreme conditions with improved convergence speed [43]. Similarly, Wang et al. developed a sliding mode controller and a nonlinear optimal tire force allocation algorithm to realize post-impact stability control for four-wheel-independent-drive electric vehicles. The presented method used a linear sliding surface to simultaneously suppress the undesired yaw rate and yaw angle, and developed a modified tire model by fusing the Magic tire model with the elliptic function to describe strong nonlinearity and coupling characteristics of tire forces [75]. Rapid stability restoration was achieved through efficient coordination of tire forces. Salfeld et al. suggested an optimal control method to maximize the resistive yaw moment by solving a nonlinear optimization problem to obtain the desired tire braking forces and front-wheel steering angle [76]. However, the control gradient was not considered and the optimization was performed offline. This leads to its limitations in actual applications due to varying post-impact initial motions and postures.

The above-mentioned control methods address post-impact vehicle stability from the perspective of vehicle dynamics but ignoring the safety problems resulting from global path deviation. Significant trajectory deviation from the target lane during the primary collision may lead to secondary collisions with other vehicles in the side lanes [98], [99].

2) Multiple Actuators Coordination Control for Environmental Safety: In the context of vehicle stability control, it is crucial to consider post-impact trajectory's safety by designing controllers that optimize environmental safety under structured road conditions.

To achieve the asymptotic stability of vehicle while avoiding secondary collisions, Wang et al. developed a fuzzy self-tuning Proportional-Integral-Derivative (PID) post-impact stability controller to coordinate front-wheel steering and differential braking [77]. The controller includes two PID units that produce an additional yaw moment based on yaw angle and a front-wheel steering angle based on lateral displacement deviation. The fuzzy logic was designed for tuning PID parameters based on the tracking error and error changing

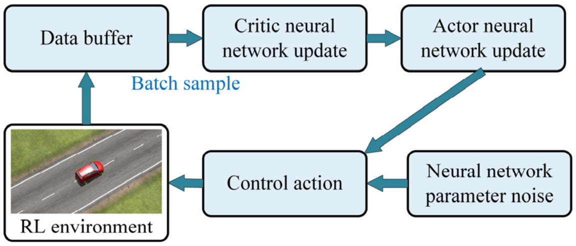

Fig. 5. Reinforce Learning-based drift controller.

rate to optimize control performance under different driving conditions. The PID controller has the advantages of simplicity and ease of parameter tuning, but it cannot achieve multi-objective optimization. Besides, there is possibility of system overshoot and oscillation, which may fail the PID controller in real-world implementation.

In contrast, neural network-based control is becoming popular as it has no requirements of physical modelling. Yin et al. designed a post-impact neural network-based drift controller based on data-driven reinforcement learning (RL) [78] (see Fig. 5). Due to the coupling relationships between multiple actuators and different vehicle motions after collision, the Depth Deterministic Policy Gradient method was employed to deal with high-dimensional continuous vehicle motion space. The controller selects the front-wheel steering angle, the front-axle driving torque, and the differential braking force at the rear axle as control outputs to reduce the yaw angle and lateral displacement deviation relative to the global path. To improve training efficiency and control performance, Hou further embedded a rule-based switching control and drift manipulation into the RL algorithm [79].

The introduction of the black-box controller simplifies the controller development process by converting complicated vehicle dynamics modeling into numerical modeling. However, the neglect of vehicle dynamics restricts its robustness to rapidly-changing driving conditions. Additionally, the limited training datasets and generalization ability may fail the neural network-based controller in unseen traffic scenarios in addition to the possibly time-consuming modeling training process.

With regards to model-based controllers, sliding mode control has gained wide attention to solve multi-objective coordination control problems. To improve the safety of the post-impact trajectory, researchers have developed regular sliding mode control [81], sliding mode control with multiple sliding surfaces [82] and second-order sub-optimal sliding mode control [80] to simultaneously regulate the lateral offset and yaw angle after initial collisions. To further enhance vehicle stability recovery, the integration of the feed-forward control and optimization-based control has been the focus of research. For example, Cao et al. proposed a compensatory MPC by integrating with the feed-forward control [83], while Li et al. combined linear quadratic regulator (LQR) and feed-forward control [84].

From the global optimization perspective, Parseh et al. proposed a collision mitigation framework that combines motion planning, vehicle dynamics modelling, and accident reconstruction to derive the trajectory with the lowest collision possibility [100], [101]. Similarly, Yang et al. designed a trajectory optimization algorithm to minimize lateral displacement [85]. To establish a 3-DOF vehicle dynamics model, they optimized four wheels' braking torques based on initial post-impact states. A cost function based on the fourth norm integral of lateral displacement is given by

$$C = \sqrt[4]{\frac{\int_0^{t_{end}} Y^4 dt}{t_{end}}} \tag{9}$$

where Y is the lateral displacement of the vehicle and t_{end} is the control period. The nonlinear problem can be solved offline to obtain the optimum control sequence using the Sequential Quadratic Programming (SQP) algorithm with the *fmincon* optimization toolbox. The results show that the maximum lateral displacement is effectively reduced compared to the traditional ESP. Yang et al. also presented a steering control scheme using the same nonlinear numerical solution method [86], [90], in which different cost functions were compared. It was found that similar performance can be achieved by only punishing the terminal velocity. Then the cost function can be modified as

$$J = k_1 \dot{X}(t_{end}) + k_2 \dot{Y}(t_{end}) \tag{10}$$

where $\dot{X}(t_f)$ and $\dot{Y}(t_f)$ are the global longitudinal and lateral velocities; k_1 and k_2 are the weighting coefficients. The modified cost function allows for the cooperative optimization of both road lateral offset and longitudinal braking distance. It can simplify the optimization problem by maintaining the continuity of the nonlinear function while avoiding the integral formulation in Eq. (9). Additionally, including the front-wheel steering increases the feasible region for resultant forces and achieves better control performance in certain scenarios.

It is important to note that while the open-loop controller derives the control sequence based on the initial post-impact states, it ignores the system modeling error and uncertain disturbance. To address this issue, Yang also developed a closed-loop quasi-linear optimal controller (QLOC) that coordinates the yaw moment and lateral force to minimize the lateral displacement [87], as shown in Fig. 6. QLOC transforms the optimal control problem into a two-point boundary value problem (2pt-BVP) according to the Pontryagin's minimum principle and endpoint constraints. The defined Hamilton function and costate equations are given by

$$\begin{aligned} &H(\boldsymbol{\lambda}(t), \boldsymbol{x}(t), \boldsymbol{u}(t)) = \boldsymbol{\lambda}^T(t) \cdot f(\boldsymbol{x}(t), \boldsymbol{u}(t)) \\ &\dot{\boldsymbol{\lambda}} = -\left(\frac{\partial H}{\partial \boldsymbol{x}}\right)^T = -\left(\boldsymbol{\lambda}^T \cdot \frac{\partial f}{\partial \boldsymbol{x}}\right)^T = -\left(\frac{\partial f}{\partial \boldsymbol{x}}\right)^T \boldsymbol{\lambda} \end{aligned} \tag{11}$$

The optimum of the original cost function can be obtained when the control function satisfies

$$\left(\frac{\partial H}{\partial u}\right)^* = 0 \tag{12}$$

where $\boldsymbol{x}$, $\boldsymbol{\lambda}$ and $\boldsymbol{u}$ are the system state, costate and control input vectors; $f(.)$ is the nonlinear transfer function that represents the system characteristics.

The online solution of 2pt-BVP requires estimating the terminal time t_f. Yang established a forward recursion-based

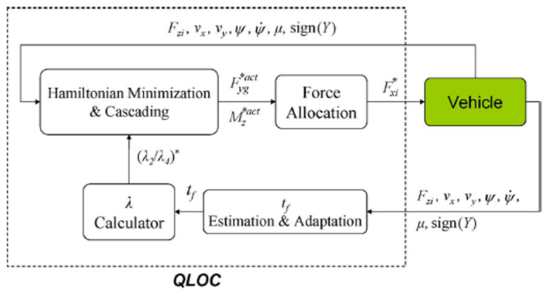

Fig. 6. The flowchart of QLOC with 2pt-BVP [87].

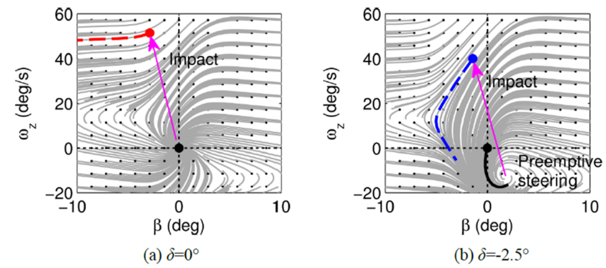

Fig. 7. The post-impact phase trajectory under pre-emptive steering [8].

strategy to update the terminal time estimation at each time step. To solve the nonlinear Hamilton function, two dynamic models were constructed. A single-track linear vehicle model was used for costate estimation with an equivalent vehicle sideslip stiffness, while a double-track nonlinear vehicle model was used for optimizing the Pontryagin function based on co-state estimation results and current states [88]. Real-time optimization was carried out through the coordination of yaw moment and global lateral force.

Yang made several improvements for the QLOC trajectory optimizer, such as adding in the steering angle to the online optimization and simplifying the control output constraint to increase computational efficiency by up to 15% [89]. To deal with changing parameters, the LTV system with the Jacobian matrix was used instead of the constant matrix for solving the optimal costate [90]. A multi-mode switching strategy was developed to improve robustness under varying collision intensities. It included the lateral force optimization mode, QLOC mode, and PID settling mode, based on the open-loop result analysis [85], [91]. Gao et al. simplified the co-state optimal estimation to enable real-world applications. The computational intensiveness was reduced by only retaining the global lateral force control mode [102]. They also developed an integration method with traditional stability control systems. The real-time performance of the integrated controller was verified under the CarMaker simulation environment.

The hazard of vehicle collisions is strongly related to the direction of the collision source. Passive safety systems such as crumple zones are designed in the engine compartment and luggage compartment of vehicle to absorb the kinematic energy and can thus effectively reduce the impact of front and rear collisions. However, there is insufficient buffer space on the sides of the vehicle body, and thereby, side collisions can directly damage the cockpit and pose a serious threat to the passengers' safety.

From this point, Kim et al. developed a LTV-MPC controller to simultaneously regulate the lateral displacement and yaw angle [92]. The cost function is constructed as

$$J = w \cdot \sum_{i=1}^{N} (Y_s(i))^2 + \sum_{i=1}^{N} \left(\left| \psi_{mod}(i) - \frac{\pi}{2} \right| - \frac{\pi}{2} \right)^2 \quad (13)$$

where w, n, and Y_s are the weighting coefficients, prediction horizon, and lateral displacement at each time step; ψ_{mod} is the modulus operation of the yaw angle and π, which is given by

$$\psi_{mod} = mod(\psi, \ \pi) \quad (14)$$

In Equation (13), the second term of the cost function ensures the vehicle yaw angle remaining parallel to the road, thereby avoiding side collisions. To construct the database of the expected terminal yaw angle, the cost function is first offline optimized based on a double-track vehicle dynamics model. Then the control objects of different terminal heading angles can be obtained according to different vehicle velocities and impact impulses through a look-up-table. The LTV-MPC and braking force allocation are designed to track these objectives. The simulation results verified the vehicle's ability to restore stability.

Kim et al. innovatively proposed a post-impact pre-emptive control strategy [4], which involves adjusting the stable region through front steering based on the post-impact trajectory shown in Fig. 7. Using the Ackerman steering theorem, this strategy enables pre-emptive steering according to the predicted post-impact yaw rate by assuming that the upcoming impact can be detected. With the post-impact controller, the vehicle can maintain better stability and remain in the stable region.

High-precision vehicle state acquisition is essential for effective controller operation. While the kinematics and dynamics based state estimation has been widely studied for vehicle stability control systems, post-impact active safety control systems present new state estimation requirements [103], especially for the accurate estimation of yaw angle and lateral displacement relative to the reference path under violent impact disturbances. Commonly used camera vision and kinematic sensors for lane detection and other auxiliary sensoring devices may also fall short under extreme conditions [104], [105], [106], [107].

To address this challenge, Kim et al. developed a fusion estimation algorithm of yaw angle and lateral displacement for post-impact stability control [108]. Using an extended Kalman filter-based state estimator in combination with a nonlinear vehicle dynamics model, a compensation algorithm was designed for camera vision. On this basis, D. Kim further designed a fault-tolerant controller for often-neglected braking failure compensation based on LQR and PID [93], with the LQR feedback control law to regulate the yaw angle error and lateral offset based on a 2-DOF model, and the PID controller to derive the maximum braking torque under partial braking failure based on the Dugoff tire model. The simulation results

TABLE III
TAXONOMY OF EXPERIMENT METHODS FOR POST-IMPACT ACTIVE SAFETY CONTROL

Experiment methods	Brief description	Advantages	Disadvantages	References
Water Cannon Experiment	Simulate the impact by generating a reverse high-pressure water jet.	The reproduction of collision scene is relatively accurate. The same experiment could be repeated.	The vehicle refitting is complicated and high-cost. Relatively high safety risk.	[112]
Kick Plate Experiment	Simulate the impact interference through lateral tire force, which is produced from a skateboard driven by a hydraulic pump.	The experiment is relative safe and doesn't need to refit the vehicle.	The experiment system is complicated. The reproduction of a collision scene relies on massive calibration	[113] [114] [115]
Precision Immobilization Technique	Originated from a vehicle chasing skill of American law enforcement agencies. Full-scale test after taking protective measures.	The most accurate reproduction of accident process. The vehicle refitting is simple.	The experiment process exists high safety risk. The same experiment is hard to repeat.	[63] [88] [116]
High-precision Driver-in-loop Simulator	An effective alternative simulation scheme which integrates cockpit, computing architecture, hydraulic units and screen.	The experiment safety could be ensured. Could cover a wider range of collision scenes and working conditions	High equipment cost. There exists relatively large error when compared with a post-impact vehicle in the real world.	[117] [118] [119]
Skidcar System	Reduce the adhesion of tires equivalently by auxiliary supporting wheels to make the vehicle more prone to instability.	Could simulate different slippery road. Reduces the collision impulse threshold that makes the vehicle enter unstable regions.	The vehicle refitting is complicated. Cannot simulate the collision scene alone.	[120] [121]

based on the Brach collision model and Carsim verified the effectiveness of this approach.

Real road environments may present complex obstacle distribution. To help address this challenge, Cao et al. developed a post-impact obstacle avoidance algorithm [94]. This algorithm uses the artificial potential field method to depict secondary collision risks with road boundaries and obstacles, facilitating the re-planning of local post-impact vehicle paths. LTV-MPC was used to track the path based on four in-wheel drive systems and a four-wheel steering chassis. However, the traditional obstacle avoidance algorithm adopted in this research better suits normal driving conditions [109]. After a collision, it is difficult for a vehicle to maintain its direction guiding ability through steering, and the nonholonomic constraints are no longer satisfied [110]. Consequently, traditional path planning may result in poor rationality and feasibility. To address these challenges, Wang et al. proposed an integrated motion planning method that uses artificial potential field and polynomial curves to simultaneously plan longitudinal, lateral, and yaw motions. But the method's computational efficiency still needs to be improved [95].

In conclusion, post-impact safety control is gradually transitioning from single-DOF control to multi-actuator coordination control. While single-DOF control schemes like post-impact braking or steering have the merits of simple design and easy implementation, they only avail for longitudinal instability or slight lateral instability. Coordination control methods using multi-actuators can achieve multi-dimensional dynamics stability recovery and cover a broader range of driving conditions. However, these methods incur high computational costs as optimization methods need to be resolved online. Additionally, exploring motion planning and stability control combinations to avoid secondary collisions in an obstacle-intensive environment is highly anticipated.

IV. EXPERIMENT METHODS FOR POST-IMPACT ACTIVE SAFETY CONTROL SYSTEM

Vehicle instability caused by collisions is dangerous. The collision itself poses a significant threat to bodily and property safety of passengers. Traditional vehicle crash experiments used to evaluate passive safety systems and body strength design are expensive and unrepeatable, and they are unsuitable for post-impact stability control verification [111]. Therefore, developing efficient experimentation methods to simulate different degrees of instability caused in various collision scenarios while ensuring the vehicle's and occupants' safety is challenging. Several experimentation methods have been proposed for post-impact stability control verification, mainly including the water cannon, kick plate, PIT operation, high-precision driver-in-loop simulator, and skidcar experiment system. Their advantages and limitations are briefly summarized in Table III.

Fig. 8. The water cannon experiment [112].

A. Water Cannon Experiment

The water cannon is an auxiliary piece of equipment used to evaluate a vehicle's post-impact stability by generating a reverse water jet. Ford Corporation first developed the equipment, which comprises a high-pressure air cabin, a high-pressure water cabin, valves, and a nozzle installed in the luggage compartment. When the test vehicle speeds up to a predetermined speed and reaches a set road surface, the valve opens to quickly release a considerable amount of high-pressure air and water mixture to one side of the test vehicle. The high-speed water-gas mixture creates a reaction force on the vehicle to mimic a rear impact collision. The experiment method is illustrated in Fig. 8.

The water cannon experiment method has simple vehicle modification and high similarity with real-world accidents.

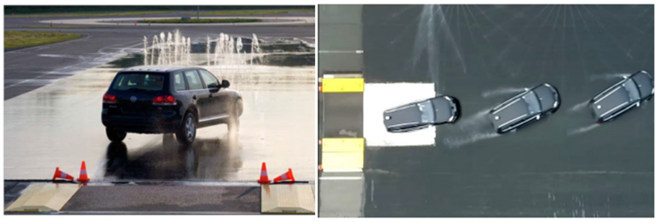

Fig. 9. The kick plate experiment [88] [114].

However, the increased load in the luggage compartment results in considerable changes in the vehicle's Center of Gravity and yaw moment of inertia. Additionally, the sudden mass change resulting from water-gas ejection can cause significant interference to the controller. The reaction impulse produced is limited so that the water cannon method can only be used to simulate minor collision situations [112].

B. Kick Plate Experiment

The kick plate device consists of a skateboard embedded into the road surface and a hydraulic pump driving the skateboard. When the test vehicle's front or rear axle rolls over the skateboard, the hydraulic-powered skateboard creates an instantaneous displacement perpendicular to the vehicle's forward direction. This sudden movement causes vehicle instability due to the low skateboard surface's friction with the tires. The unstable vehicle then drives on various road surfaces to evaluate the post-impact controller's performance under different road adhesion conditions. This process is illustrated in Fig. 9.

Although the kick plate equipment system is complex and expensive, the high safety and repeatability features make it competent for simulating different levels of impact intensity under various road surfaces. Thereby, it is widely used to test the reliability of vehicle control systems. For instance, Kamann et al. employed a single-track vehicle dynamics model to analyze how the kick plate's lateral force affects a vehicle's yaw motion. Additionally, the kick plate experiment is also utilized to evaluate the reliability of radar sensors under severe conditions and to assess the impact of excessive yaw motion on obstacle detection algorithms [113]. The kick plate experiment can also examine driver's reactions during sudden vehicle instability, thus facilitating the optimization of safety control [114]. For instance, Francesco et al. conducted a kick plate experiment under extreme conditions and collected the driver's steering wheel torque under emergency conditions to optimize the design of active steering assistant systems [122]. Similarly, Mehrjerdian et al. analyzed the control performance of an assistant driving system and its improvement in the driver's subjective feelings under emergency conditions activated by kick plate experiments [123].

The verification effectiveness of kick plate experiments depends on several factors, including the plate adhesion condition, lateral plate speed, initial vehicle speed and the like. Z. Lozia developed a vehicle dynamics and kinematics model that considered the plate's lateral displacement interference and summarized the impacts of various plate impact impulses and different impact-exposed axles [124]. The initial vehicle speed configuration is employed to achieve the desired destabilizing effects [115]. Beltran et al. introduced a calculation method to determine the actual action time of kick plate experiments by accounting for the hydraulic pressure setting and plate acceleration time [112].

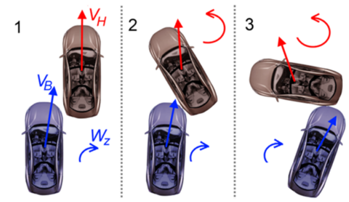

Fig. 10. The schematic of the Precision Immobilization Technique [112].

C. Precision Immobilization Technique

The Precision Immobilization Technique (PIT) is a common vehicle pursuit maneuver utilized by American law enforcement agencies. It is used to safely force a target vehicle to stop, particularly when the vehicle is driving at high speeds, while minimizing the risk of the violent impact. The PIT maneuver involves the host vehicle approaching the target vehicle from one side, with the front of the host vehicle making close contact with the rear of the target vehicle. The host vehicle then impacts the target vehicle by rapidly steering, causing the rear axle of the target vehicle lose propulsion force and enter an unstable state. The resultant vehicle dynamics instability ultimately forces the target vehicle to stop [63] as shown in Fig. 10.

PIT can also be used as a verification method for post-impact active safety control by taking protective measures in advance on the test vehicle. To ensure that the experiment is effective, the intended impact position of the test vehicle can be covered with steel skin, and the host vehicle's damage can be reduced by using soft plastic materials [88]. Beltran et al. analyzed the safety range of impact impulses for PIT and proposed that the tail and side impact impulses should not exceed 6500 Ns and 2500 Ns, respectively. They also summarized the post-impact vehicle's state distribution in the phase plane under these impulse constraints [112]. In another work, David et al. designed a PID-controlled automatic execution system for PIT to avoid bodily injury during experiments, which serves as a reference for unmanned post-impact stability control experiments based on PIT [116]. Furthermore, Rohit et al. utilized the Relaxed A* path planning method to promote the automation of PIT operations [125]. These studies aim to reduce the safety risks associated with PIT-based verification for post-impact active safety control.

D. High-Precision Driver-in-Loop Simulator

The high-precision Driver-in-Loop simulator is a viable alternative for real vehicle experimentation. Unlike Software-in-Loop simulations, the Driver-in-Loop simulator can access the driver's signals in real-time, including steering wheel inputs, acceleration/brake pedal positions, and other maneuvering instructions. It then feeds back visual information and vehicle response signals to the driver based on a high-precision

Fig. 11. The S2 simulator [128].

Fig. 12. The SIM4 simulator [92].

vehicle dynamics model [126]. This mechanism enables the Driver-in-Loop simulator to account for the influence of driver's response delay on vehicle motion [127]. Representative Driver-in-Loop simulators suitable for post-impact instability simulation include the S2 simulator developed by the Chalmers University of Technology and the SIM4 simulator developed by the Swedish National Road and Transport Research Institute (VTI) [117], which are shown in Figs. 11 and 12, respectively.

The S2 simulator features a 6-DOF platform, a cockpit, and a computing architecture. The 6-DOF platform, jointly driven by six hydraulic units, can simulate vehicle attitude changes, body shaking, and noise effects. The cockpit features a virtual display screen connected to the driver, providing visual feedback of the driving scene. The computing architecture comprises four computing units responsible for driving scenes, vehicle dynamics, moving platform, and image and sound processing, respectively [128]. Meanwhile, the VTI's SIM4 simulator is built on an 8-DOF platform, which has two orthogonal tracks beneath a 6-DOF platform. This construction significantly expands the horizontal moving range. In addition, the cockpit display screen's visual angle is extended to 210 degrees, improving immersion [119].

Both simulators have shown effectiveness in verifying post-impact active safety controllers. For instance, the SIM4 simulator was used by Yang et al. to test the effect of post-impact stability controllers, and the results showed that the controller's intervention alleviated the driver's sense of urgency while decreasing their maneuvering pressure under extreme working conditions [118]. Meanwhile, Kusachov et al. compared the control effects of post-impact active braking control systems with S2 and SIM4 simulators. Their study found that the SIM4 simulator's smaller steering stiffness enabled the driver to conduct more radical steering operations, and this allowed the vehicle to regain stability more quickly [117].

Beltran's analysis of the post-impact state distribution region concludes that the Driver-in-Loop simulator can cover a more extensive range of working conditions than other real vehicle experimentation methods. However, the limitations come from the driver's acceleration endurance and hydraulic actuator's performance. Additionally, the scene rendering level is not very high, and the simulator's ability to simulate real accidents needs improvement [112].

Fig. 13. The skidcar system [129].

E. Skidcar System

The skidcar system was initially developed in Sweden. This system installs two steel beams on the front and rear sides of a modified chassis. Auxiliary supporting wheels with hydraulic lifting devices are arranged at both ends of the steel beams. These wheels can roll freely around Y and Z axes, as shown in Fig. 13. During experiments, the hydraulic device partially lifts the vehicle body through the auxiliary supporting wheels. This action transfers part of the vehicle's gravity to the auxiliary supporting wheels. However, the free-following supporting wheel cannot provide any friction, assuming that rolling friction is negligible. Consequently, the adhesion of the vehicle tires is reduced so as to simulate the low-adhesion driving conditions such as snow, ice, and wet roads [120].

The skidcar system is widely used by Original Equipment Manufacturers to test the performance of ESC and other active safety systems due to its ease of installation and high safety. The system can simulate various extreme driving conditions without the need to configure specific snow and ice road scenes [121]. On this regard, Vidas et al. established a 7-DOF vehicle model for a modified vehicle equipped with the skidcar system. They analyzed the roll motion and steady-state steering characteristic changes of the vehicle in both the frequency and time domains. The results indicated that the vehicle equipped with auxiliary wheels had similar dynamic characteristics with the original vehicle [129]. The skidcar system reduces the threshold of collision impulse that would make the vehicle enter the unstable state. When combined with other experimentation methods mentioned above, the skidcar system can effectively expand the distribution area of the post-impact vehicle states [112].

In summary, there are several experimentation methods available for post-impact safety control verification. Both the water cannon and kickplate can safely simulate a collision impact; but their high costs and complicated structures still impede their wide applications. The PIT operation that originated from a vehicle chasing technique can replicate a specified collision scene to the maximum extent; but ensuring sufficient protection and experiment reproducibility is challenging. High-precision simulators are effective alternatives to real vehicle experiments; but their efficacy is still in doubt.

The skidcar system is a useful tool for simulating different slippery road conditions and for reducing the collision impulse threshold. Combining the skidcar system with the water cannon or kickplate is a promising approach for post-impact safety controller experimentation.

V. Conclusion and Prospects

Despite of significant advancements in autonomous driving and active safety control techniques under normal driving conditions in past years, it is equally important to improve vehicle safety and stability after a collision to reduce casualties in road accidents. Continuous technical developments have made it possible to introduce more advanced control algorithms for post-impact active safety control. In this paper, we have systematically reviewed current active safety control systems for post-impact vehicles, focusing on collision modeling, post-impact stability control, and experiment methods. While significant progress has been made in post-impact active safety control, our analysis has identified several promising directions for future research.

A. Collision Model for Post-Impact Safety Controller Development

An appropriate collision model is imperative to developing enabling post-impact safety controllers by adequately reconstructing different collision scenarios and accurately describing vehicle dynamics. The traditional FEM primarily focuses on assisting in vehicle body design. While this method can accurately depict collision force changes and vehicle body deformation, it requires high computational intensiveness and is unable to account for vehicle dynamics. On the other hand, the macroscopic momentum conservation-based collision modeling method suffers from significant modelling errors under certain scenarios, and high-precision modeling and simulation methods for controller verification are absent. A combination of reduced-order collision models and recursive momentum conservation on a micro-timescale can form a collision model that both ensures high computational efficiency and retains key deformation characteristics. It is promising to establish a competent collision model needed for post-impact stability controller development in near future.

B. Vehicle State Estimation Under Disturbance of Collision Impact

State estimation under the disturbance of collision impact is challenging given the high-intensity instantaneous impact during collisions. The impact can cause significant interference with onboard sensors. For instance, the sudden distortion of camera images caused by a collision can lead to the vehicle losing its lane line detection ability. Moreover, the impact force can also give rise to significant errors in the underlying vehicle dynamics model, and thus fails onboard state estimation algorithms. Therefore, it is necessary to develop a high-accuracy vehicle model that has strong robustness to external disturbance to enhance state and parameter estimation.

C. Efficient Coordination Control of Multiple Actuators Under Extreme Conditions

Achieving efficient coordination control of multiple actuators under extreme conditions is necessary for post-impact stability control. It is a typical multi-objective optimization problem as the longitudinal and lateral tire forces have a tightly coupling relationship and exhibit highly nonlinear characteristics under extreme working conditions. The coupling relationship and nonlinearity result in complicated vehicle dynamics subject to varying working conditions. It is difficult for a single actuator to achieve multi-objective optimization, and the strong coupling and nonlinearity tire forces can significantly compromise the optimization derivation speed. As a result, it is crucial to study how to effectively coordinate redundant control freedoms, considering tire force coupling and actuator dynamic response characteristics. Additionally, it is essential to study the reconfiguration of the workable actuators after collision to improve fault-tolerant performance.

D. Motion Planning for Secondary Obstacle Avoidance

Motion planning for post-impact vehicles presents a significant challenge given the complicated road environment that features various obstacles and significant hazards for secondary collisions before restoring vehicle dynamics stability. To minimize the risk of possible secondary collisions, introducing motion planning into active safety systems to realize the coordination of stability control and secondary obstacle avoidance is essential. Current research predominantly aims to optimize the lateral lane offset and the end yaw angle of vehicle from an empirical perspective, but invariably neglects the positions of obstacles. Moreover, the vehicle often falls into unstable conditions such as sharp sideslip and drifting, following a collision. Traditional path or trajectory planning methods that function with nonholonomic constraints may be no longer valid. Therefore, it is essential to develop motion planning methods that can be implemented in post-impact active safety control.

E. Safe and Effective Full-Scale Experimentation Methods for Post-Impact Safety Control

Testing the effectiveness and reliability of a developed post-impact control system presents special requirements for experimentation, given the high cost and hazards of the impact process in human-in-loop tests. Designing an appropriate experiment method to simulate the unstable state of the post-impact vehicle while ensuring safety and repeatability is highly desirable. Combining the skidcar system with the water cannon or kick plate device to generate virtual impulses under different equivalent road adhesion coefficients is an effective way to carry out collision experiments for post-impact safety controller verification.

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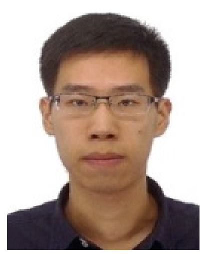

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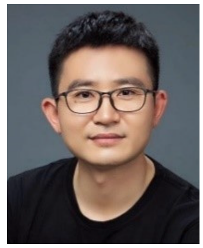

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