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TOPICAL REVIEW

Vehicle State-Based Control for Modern Automotive Platforms: Bridging Research and Industrial Applications

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ABSTRACT Recent advancements in control technologies, sensor availability and intelligent actuators have driven the development of Integrated Vehicle Dynamics Control (IVDC). This approach offers a unified framework for managing complex interactions between subsystems, enabling enhanced safety, performance and adaptability features. However, practical implementation and widespread diffusion of this technology remain a significant challenge due to the lack of standardized strategies and heterogeneity of components, with a significant gap between academic descriptions and automotive industry practices became evident through analysis of over 300 sources from scientific literature, industrial patents, and OEM documentation. This work aims to investigate the applicability of IVDC within existing vehicle architectures and address the need for a real-time adaptive control solution. A systematic examination of subsystem coupling mechanisms, industrial applications and the influence of different vehicle morphologies on the choice of control architecture are discussed. Moreover, alternative approaches, such as decoupled control and multi-agent systems, are introduced as potential solutions to overcome limitations of conventional coordination schemes. Finally, emerging perspectives on system adaptability, with particular emphasis on stability-oriented design and the enabling role of Vehicle-to-everything (V2X) communication, are discussed. Even considering a limited availability of comparable quantitative metrics from OEMs due to proprietary considerations, the overall intention is to provide a comprehensive and pragmatic outlook on the evolving boundaries of IVDC, based on rate of usage metric as a function of actuator type and availability, considering its alignment with current and future market demands.

INDEX TERMS Vehicle control, integrated control, actuators, stability, decoupling, automotive platforms, autonomous driving, V2X.

I. INTRODUCTION

Since the early 2000s, researchers have recognized the imperative for a comprehensive exploration of integrated vehicle control, driven by the advancement of sophisticated control systems and the expanding accessibility of diverse sensors [1], high-precision actuators, and increasingly robust ECUs, whose accuracy and efficiency have been enhanced by emerging enabling technologies [2], leading to an exponential growth in the number of application studies published in journals. In this context, while on the one hand these factors contribute to OEMs offering distinctive features to the market as the main added value to promote new vehicles, on the other hand, the increasing level of automation [3] required for sophisticated driving assistance systems forces the development of ever stricter regulations to ensure adequate

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levels of reliability and adaptiveness to multiple dynamical scenarios.

Several studies, already presented in this context [4], [5], meet the need to provide the information required to design complex control systems, fed with a multitude of new deeply interconnected smart sensors of the autonomous vehicle industry. Starting from data gathered by multiple sensors, distributed over the vehicle, the concept consists of fully perceiving the state of the system and then of translating the desired control actions through the various actuators, addressed in the preliminary design phase of the vehicle. Given the virtually infinite array of configurations of sensors, actuators, and control systems and the inherently dynamic nature of vehicle control systems, there is a pressing need for integrated solutions developed through a unified, systematic, and methodologically rigorous approach.

Despite the obvious benefits of IVDC (Integrated Vehicle Dynamics Control), including reduction of the number of sensors and actuators, fault-tolerance structure design, the currently proposed cooperative approaches directly generate redundancies in control problems, leading to significant challenges in optimal allocation tasks [6], [7].

Although multiple approaches based on varied architecture layouts have emerged to guide individual systems toward a common target, the search for an optimal, standardized solution remains elusive, which has unsurprisingly drawn intense focus and scrutiny from the scientific community. Indeed, much of the existing research focuses on a deep analysis of coordination approaches — evaluating systems' every degree of freedom and establishing criteria to classify various integrated vehicle control strategies. While these studies provide valuable theoretical insights, they often fall short of addressing the practical challenges and, though prominent industry players have demonstrated IVDC concepts [8], [9], [10], the literature consistently indicates that the path to fully integrated, real-time control remains largely uncharted. To this purpose, this research aims at offering insights into the applicability of IVDC for existing vehicle structures and explores new frontiers in achieving real-time adaptive control architectures, while also presenting an overview of industrial applications and alternative control solutions beyond the traditional hierarchical coordination approach. If on one hand, the need for a systematic coordination of more subsystems, according to global control objectives and actions, in terms of both software and hardware, rather than simply combining the subsystems all together, still remains an open and strongly monitored unresolved problem for OEMs, tier1s and researchers in the automotive industry, on the other hand, a comprehensive literature analysis (300+ citations from academic journals, industrial patents, OEM technical documentation, and conference proceedings, as shown in Fig. 1) revealed a fundamental challenge: quantitative performance metrics from industrial implementations are rarely available or comparable due to proprietary protection and heterogeneous testing conditions. Consequently, with the objective to provide actionable guidelines for system selection rather than purely theoretical benchmarking, the proposed analysis framework evaluates integrated control architectures based on: (i) rate of usage as a function of available actuators and vehicle morphology; (ii) Technology Readiness Level (TRL) assessment and market deployment status; (iii) qualitative engineering trade-offs including complexity, integration level, cost implications, and reliability.

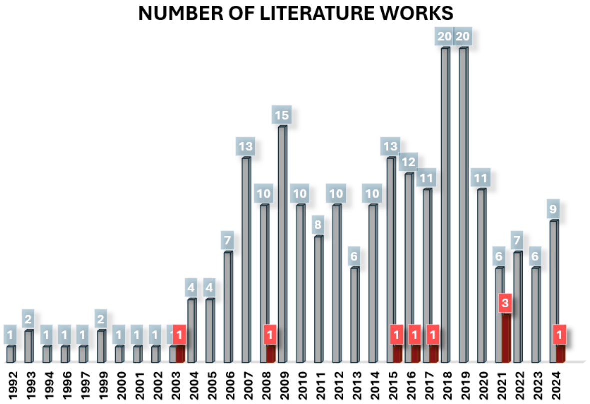


FIGURE 1. **Number ofliterature works and relatedreview articles published from 1992 to 2024. The x-axis represents the publication year, while the y-axis indicates the number of works identified. Data were collected from Scopus and IEEE Xplore databases using the query criteria "vehicle dynamics integrated control", "integrated chassis control", "integrated vehicle control," "coordinated chassis control", and "hierarchical vehicle control."**

Table 1 reports the temporal distribution of research and review articles, with early works establishing the necessity of integrated control as control functions and actuators proliferated, and introducing a foundational classification and coordination strategies that explicitly include driver and environment within the integrated structure [11]. The taxonomy was then revisited from a control-direction perspective (longitudinal, lateral, vertical), offering an initial mapping despite limited formalism and emphasizing accurate tyre/vehicle models, tyre-limits consideration, and camber/toe objectives in light of x-by-wire diffusion [12]. This viewpoint remained influential as [13] systematized X/Y/Z coordination ("any two" and "three" subsystems), identified the lack of guidance on architecture choice, and proposed single- versus multi-criterion classifications. Persistent gaps emerged: predominance of offline/HIL validation, absence of benchmarking for overall integrated behaviour in complex manoeuvrers, and insufficient analysis of coupling mechanisms foundational to advanced coordination. A dynamics-grounded advance formalized subsystem couplings [14], while downstream/upstream criteria were introduced and compared, stressing applicability, standardization, and adaptability [15]. A comprehensive synthesis later covered recent coordination structures (feedback, feed-forward, intelligent) and addressed integrated performance evaluation limits [16]. With x-by-wire expansion [17], [18] and autonomous development, [19] reviewed two-/three-subsystem integrations, highlighting driving-condition identification, modular multilayer coordination, and gaps in critical-condition and fault-tolerant control; path-tracking surveys deepened sensing, reference generation, and hierarchical architectures [20]. Despite progress, industrial, in-depth applications remain scarce: practically, market-ready IVDC must adapt swiftly to changing scenarios [21], [22], but accurate designs hinge on parameters sensitive to operating conditions [23], [24], whereas less model-based routes require extensive data; adaptiveness links to perception for safety-critical tasks [25], [26], [27] and to V2X-enabled connected mobility [28]. Multi-level solutions mixing model- and data-based layers seldom clarify where physical models are essential; complex nonlinear designs face real-time limits [29] yet motivate burden-reduction strategies [30] and stability-based coordination [31], [32], [33]. Consequently, IVDC design should be morphology- and actuation-driven especially in EVs, where precise DoF control is not only necessary but also feasible [34], but actuation-oriented classifications are still lacking. Beyond hierarchical approaches, decoupling strategies (notably for in-wheel EVs [35], [36], [37] and robust/adaptive/fuzzy/inverse variants [38], [39], [40]) remain under-explored in IVDC, while distributed multi-agent methods [41], [42], [43] can reduce computational burden and system complexity. These open issues motivate a pragmatic, market-aligned delineation of emerging research boundaries, highlighting multiple relevant still-open issues and adding complexity towards the route of integrated control schemes employment.

The following article's contributions can be summarized as:

- description of the vehicle sub-systems coupling mechanisms along with a systematic investigation on industrial applications related to vehicle integrated control. The former will help building the foundations for a clear understanding of the vehicle, not only as an intrinsically coupled subject but also as a living actor within a complex environment. While the latter will aim at unveiling the gaps between research and practical implementation;
- definition of common vehicle morphologies and the investigation on how the design of integrated controller is deeply influenced and should be thought based on those structures, with a critical eye for the upcoming scenario of electric mobility;
- analysis of the alternative control methodologies, including decoupling and multi-agent strategy towards overcoming issues related to classical integrated control approaches;
- newer perspectives based on the nature of the system to be controlled, exploiting stability regions, the adaptiveness property of IVDC systems and the upcoming V2X scenario. The latter being regarded as a promising technology enabler with increased available data.

The paper is, therefore, structured as follows: Section II describes the vehicle coupling mechanism, while the academic and industrial bibliography investigation is introduced in Section III; vehicle morphologies and actuators are discussed in Section IV. The presentation of alternative decoupling control methodologies can be found in Section V, while future research directions are described in Section VI. Finally, the conclusion and discussion part is formalized in Section VII.

II. MODELLING CHALLENGES OF THE VEHICLE SYSTEM

Even in its nominally passive state, a vehicle chassis is a tightly interwoven, six-degree-of-freedom body: lateral, longitudinal, vertical, roll, pitch, and yaw motions constantly influence one another. The generally intended subsystems include steering, braking, powertrain systems, suspensions and wheels, while the driver can be considered as an active subsystem, injecting three main control inputs (throttle, steer, brake). Environmental disturbances (weather, road conditions, cross-winds or other external forces) and the sheer variety of power-train architectures further contribute towards adding complexity in explaining the different coupling mechanisms. Once individual controllers, their actuators, and higher-level supervisory algorithms are layered on top, the coupling intensifies from intricate to bewildering. As escalating complexity makes even basic analysis, let alone optimization, via isolated or purely hierarchical designs untenable, a thorough re-examination of integrated vehicle-control theory becomes indispensable.

To encompass all aspects of the discussed coupling mechanisms and provide a comprehensive analysis, this section is divided into three key domains: those intrinsic to vehicle dynamics, those arising from external factors, and those dependent on powertrain morphology.

Conventionally, the coupling mechanisms associated with vehicle dynamics are defined by the chassis coupling mechanisms and the nonlinear behaviour of tyres, which indirectly affect the relationship between control inputs and vehicle motion along and around the three principal directions.

In vehicle systems, the linkage between sprung and unsprung masses (through suspension systems) results in known interactions between chassis' DoFs, when steering (braking), roll (pitch) motion occurs. Vehicle roll motion has been widely studied as a major cause of incidents [44] and various controllers aim at mitigating the tendency of a vehicle to rollover [45], [46]; however, vehicle roll hardly influences tyre and vehicle dynamics. Furthermore, roll motion impacts steering kinematics parameters and vehicle lateral and yaw dynamics due to coupling mechanisms. As for the pitch motion, an appropriate tuning of the suspension's parameters (stiffness and damping) can result in desired pitch behaviour of the vehicle [47]. Recently, Tunay et al. [48] introduced the necessity of adding the roll dynamics for specific heavy ground vehicle applications. Different mass distribution within electric vehicles should also be considered in this context. Additionally, the infrastructure and its possibility to exchange information with the vehicle will

TABLE 1. Review articles on integrated vehicle control.

Review article	Year	Subjects covered	Highlighted gaps
[11]	2003	Necessity of IVDC, application area, classification (centralised/decentralised/multilayer), control strategies, coordination control, requirements for IVDC	Role of the driver and external environment
[12]	2008	State of the art, classification (centralised/decentralised/multilayer), coordination (longitudinal/lateral/vertical)	Precise tyre and vehicle models for coupling and tyre non-linearities, description of tyre force limits, camber/toe effect, and x-by-wire technologies
[13]	2015	Classification in x, y, z directions; in-depth integration (x+y, x+z, etc.); classification (single vs multi-criterion)	HIL implementation, benchmarking criteria (e.g., energy consumption, global performance) in complex motion cases
[14]	2016	System coupling, classification (centralized, decentralized, multilayer), examples	The adoption of full vehicle models, integration of multi-sensor information, fault-tolerance property, driver influence, estimation of road parameters.
[15]	2017	Classification (centralised/ supervisory/ hierarchical/ downstream/ upstream, single-/multi-criterion), comparison between methods	Real vehicle implementation, adaptability (e.g., same manoeuvrer, different driving feeling)
[19]	2021	Driving condition identification, integration of any two or all three subsystems	Coordinated control under critical driving conditions, fault-tolerant control, and motion planning
[16]	2021	Architectures (downstream, upstream), reference tracking, coordination strategies, control allocation, control structures (feedback, feed-forward, intelligent), performance evaluation	Real vehicle implementation, trends: electric powertrains with multiple motors, integration with energy management, automated driving, comfort, motion sickness, personalization
[20]	2024	Path tracking control, architectures (centralised, decentralised, upstream, downstream), sensing, estimation, reference generation, control methods, hierarchical control	Lack of real/X-in-the-loop implementations, weak coupling between tracking and integrated control, no perception in path tracking

become intimately linked with the vehicle behaviour [49], [50].

Braking or steering action also changes the longitudinal and lateral acceleration states, thus inertia forces change and this directly promotes a redistribution of the vertical dynamic load on the wheels, so that lateral/longitudinal tyre forces are changed, in their turn directly influencing lateral and yaw motion of the vehicle. The phenomenon of vertical load transfer affects lateral and roll stability in a nonlinear manner [51]. Furthermore, studies suggest the investigation of dynamic responses of roll- and pitch-plane-coupled suspension systems for enhanced ride and handling performances [52].

The interaction between tyre and road is crucial in vehicle dynamics context, therefore different formulations have been proposed, highlighting high non-linearities between longitudinal (lateral) tyre force and tyre slip ratio (angle) and vertical load. The deeply interconnected nature of lateral and longitudinal interaction forces can be described through the concept of the friction ellipse [53] (e.g., lateral force decreases when longitudinal slip increases). As mentioned before, there are several contradictions [51] between coupled DoFs, mainly due to tyre-road coupling effect. Indeed, during cornering, the vehicle with higher lateral stability possesses a higher risk of rollover due to the fact that high adhesive capacity of tyres translates into increased possibility of maintaining driving trajectory, but greater lateral forces lead to enhanced risk of rollover. In addition, the vertical coupling between tyre and road is a factor that influences this phenomenon through modification of tyre lateral force and vehicle body roll motion [51].

Additionally, it is essential to consider the coupling relationships arising from the vehicle's interaction with external forces. The most evident example consists of the interaction with road pavement, which is characterized by unique adhesion properties and a peculiar uneven profile. Furthermore, vehicles are subjected to aerodynamic forces with numerous studies focusing on the interplay between vehicle lateral and yaw dynamics and these forces [54], [55], [56], [57]. These investigations underline that the

TABLE 2. List of symbols/acronyms and their description.

Symbol	Description	Acronym	Description
X	X position of vehicle's CG in global frame	4WS	4-Wheel Steering
Y	Y position of vehicle's CG in global frame	4WD	4-Wheel Drive
Z	Z position of vehicle's CG in global frame	ASS	Active Suspension System
V_x	Longitudinal vehicle velocity	SAS	Semi-Active Suspension System
V_y	Lateral vehicle velocity	ABS	Anti-lock Braking System
a_x	Longitudinal acceleration	TCS	Traction Control System
a_y	Lateral acceleration	DYC	Direct Yaw Moment Control
a_z	Vertical acceleration	ESP	Electronic Stability Program
m	Vehicle mass	AFS	Active Front Steering
I_z	Yaw moment of inertia	ARS	Active Rear Steering
F_x	Tyre longitudinal force	EPS	Electric Power Steering
F_y	Tyre lateral force	DB	Differential Braking
F_z	Tyre vertical force	DS	Differential Steering
Fy_f	Tyre front lateral force	BTD	Brake Torque Distribution
Fy_r	Tyre rear lateral force	CDC	Continuous Damping Control
M_x	Moment/torque around x-axis	AD	Active Differential
M_y	Moment/torque around y-axis	ARC	Active Roll Control
M_z	Moment/torque around z-axis	TV	Torque Vectoring
α_{ij}	Wheel slip angle	LKA	Lane Keeping Assistance
$\alpha_{f/r}$	Front/rear slip angle	LCA	Lane Change Assist
δ_f	Front steering angle	LDW	Lane Departure Warning
δ_r	Rear steering angle	ASR	Anti-Slip Regulation
β	Vehicle sideslip angle	FWS	Front Wheel Steering
$\dot{\beta}$	Derivative of vehicle sideslip angle	RWS	Rear Wheel Steering
V_{wheel}	Wheel velocity	AS	Active Steering
r	Yaw rate	SBW	Steer-by-wire
$\dot{r}$	Yaw acceleration	SMC	Sliding Mode Controller
CG	Vehicle center of gravity	MPC	Model Predictive Controller
θ	Roll angle vehicle	FF	Feed Forward
ϕ	Pitch angle vehicle	FB	Feed Back
ψ	Yaw angle vehicle	PP	Phase Plane
M_d	Disturbance torque	AHV	Articulated Heavy Vehicles
ω_{ij}	Wheel angular velocity	LUT	Look-Up-Table
P_b	Brake pressure	DD	Distributed Drive
$T_{steering}$	Torque applied on the steering wheel	NMPC	Nonlinear Model Predictive Control
k_{ij}	Wheel slip ratio	DBW	Drive-by-wire
χ	Heading angle		
T/M_{ij}	Torque at ij wheel		
l	Vehicle wheelbase		

aerodynamic coupling is strongly dependent on the type of vehicle, whether passenger or heavy, while in motorsport, the impact of aerodynamics on longitudinal and lateral dynamics remains a topic of wide interest [58], [59].

Lastly, the adoption of an electric and hybrid powertrain introduces additional strong coupling between vehicle dynamics, energy management and thermal state of the subsystems. The powertrain is closely linked to the braking system and the battery: a great example is regenerative braking, which is usually responsible for energy efficiency and its operation is concurrent to friction braking [60]. Depending on the type of traction (front or rear), the braking action could lead to loss of adherence or under/over steering effects. The state of charge and the thermal state of the battery should also be considered as they deeply influence traction/braking performance, potentially leading to vehicle instability when the battery works in a non-optimal operating range. Furthermore, although the promising in-wheel-motor solutions offer fast and accurate control, eliminating the mechanical transmission system, vibration and noise issues are generated [61]. Along with that, the increased unsprung mass will modify the load distribution of tyres and the overall ride quality.

An overview of all described factors and their interrelationships is presented in Fig. 2: it becomes clear that to fully capture the described interconnections among subsystems, it is crucial to develop accurate vehicle models across different operating domains. On the other hand, control-oriented modeling has become prevalent in the automotive industry because it strikes an optimal balance between faithfully reproducing a real system and maintaining a manageable computational burden. The literature presents a variety of vehicle models, ranging from high-degree-of-freedom representations [62], [63] to rigid multibody [64] and finite element [65] models. While these models are effective for analytical purposes, they frequently introduce numerical challenges when applied to control design. Therefore, models must be reduced in order, while still adequately representing the vehicle's various components, and over the past decades, extensive research has been conducted on modeling vehicle frameworks and their subsystems [66], [67], with linearization emerging as the most commonly employed method for reducing the complexity of nonlinear systems. However, this technique is still generally confined to moderate and low-speed conditions, rendering it unsuitable for addressing high-risk, nonlinear driving scenarios.

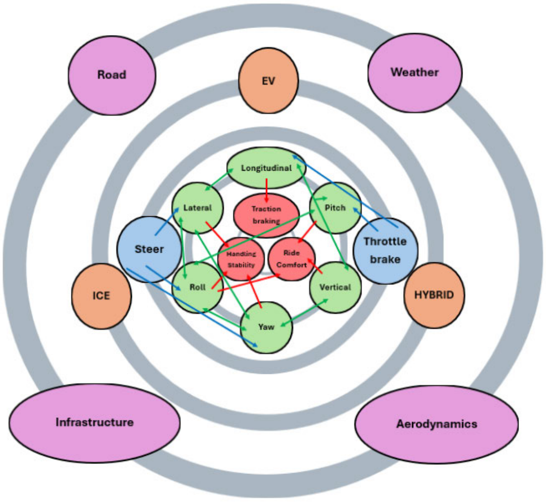


FIGURE 2. Coupling of vehicle subsystems. Objective, Movement, Driver input, Environment, Powertrain architecture.

III. ACADEMIC AND INDUSTRIAL BIBLIOGRAPHY INVESTIGATION

A comprehensive review should first define a clear methodology for systematically searching original sources that underpin the study's dissemination. As illustrated in Fig. 3, research articles from the academic field were categorized based on control direction, macro target and level of subsystem integration by querying popular research portals with same keywords listed in Fig. 1, resulting in more than 250 peer-reviewed articles, conferences, and journal publications meeting the research criteria.

The control direction criteria were chosen primarily for their universal applicability and ease of identification across diverse sources: among these, lateral control stands out as the most commonly employed form of integrated control, primarily involving the coordination of various active systems (AFS, DYC, ESP), where "integrated" refers to the collective coordination of subsystems aimed at controlling lateral vehicle dynamics. In many cases, integration is explored between two subsystems (lateral/longitudinal or lateral/vertical), often with a roll prevention term incorporated into the objective function; however, only a few studies address the integration of three or more subsystems. From the industrial context, it is necessary to gather information on the major industrial players/OEM applications within the integrated control field, including white papers, patents, technical documentation and official company's websites from 1995 up to the present time, and a general overview of the findings is proposed in Table 3.

The first, largely cited approach was the Vehicle Dynamics Control (VDC) System of Bosch [68]. The necessity of controlling vehicle motion in emergency situations was a primary concern, especially for normal drivers. The system was meant to act on engine torque and wheel brake pressure to minimize errors between target and actual motion of the vehicle. Vehicle handling was associated with the unexpected driving conditions (e.g., with large vehicle slip angle, or in the nonlinear region of the yaw rate transfer function with respect to the steering angle), with the result of a driver-friendly experience at the physical limit of tyre-road adhesion. It was the work of [69] that inspired Bosch to combine available control systems (four wheel ABS/ASR) to develop the VDC strategy. Inputs from the driver (steering wheel angle, engine drive torque) are used to define the nominal motion of the vehicle, while the lateral behaviour is represented by yaw rate and vehicle slip angle (respectively acquired from a yaw rate sensor and a lateral acceleration sensor, whose values will then be fed into an observer). Subsequently, wheel speed sensors, brake pressure sensor are added. The control logic is described by two feedback loops, one acting on the wheel slip and the other on the vehicle. The outer loop controller is designed on the Riccati method and its output is the nominal yaw moment, which is then converted into the required change in the nominal slip value of each tyre. The inner loop (slip controller) consists of a brake slip controller and a drive slip controller, depending on the working condition, one of them will be used. The brake slip controller will employ the nominal value (fed by the outer loop) and an estimation of the actual tyre slip to determine the nominal brake torque value using robust PID algorithm. On the driven wheels, the engine drag effect is also considered and converted into a nominal active drive torque. Finally, the pressure modification in the wheel brake cylinder is obtained and converted through an inverse actuator model. The drive slip controller, instead, is used only on the driven wheels; its outputs are the nominal brake torques of the driven wheels, the nominal engine torque, and the nominal value of the engine torque by means of spark retard. This subsystem also employs a nonlinear PID controller.

Subsequently, the Unified Control of vehicle using force and moment was proposed by Delphi [70], [71]. The key point was to control the authority of each active chassis system and determine their activation based on control influence coefficients. The patent refers to vehicles equipped with two or more systems (ABS, AFS, ARS, active roll bar, active suspension), each of them capable of influencing vehicle behaviour in the yaw plane. The approach can be summarized in three steps: i) the termination of corrective net force inputs and moment, ii) determination of the vehicle working region (linear or nonlinear), iii) if the vehicle is in nonlinear region, a role for each subsystem is determined. The control architecture includes a supervisory controller and a plurality of sub-controllers. The supervisory controller has the role of coordinating each system; for this purpose, the unified method requires that the effects of each control action should be expressed in terms of the same physical quantity (e.g., yaw moment). The forces and moments considered are the only ones that have an effect in the yaw plane (F_x,F_y,M_z), while through a driver interpreter system the desired motion is derived (in terms of accelerations) from the knowledge of steering, brake, throttle inputs and estimated velocity. During normal working conditions, the vehicle will be controlled through feed-forward control while a feedback part will be activated if there is a large gap between measured vehicle variables and the desired ones. This latter method will determine the variation in torque and forces using PID control; these changes, however, will be applied through the use of steering, braking and suspension actuators. To this end, the remaining force available for the control needs to be evaluated with the following widely adopted pipeline:

- estimation of the roll angle (with the knowledge of lateral acceleration, roll stiffness, roll moments and vehicle parameters);
- calculation of the normal load at each tyre;
- determination of the tyre longitudinal and lateral forces per axle and per tyre;
- evaluation of the efficiency of each tyre and the available force F_{rem}:

$$e = \frac{\sqrt{F_x^2 + F_y^2}}{\mu \, N} \tag{1}$$

$$F_{rem} = (1 - e)\,(\mu \, N) \tag{2}$$

where e is the efficiency, μ is the friction coefficient and N is the total vertical load, determined per tyre.

Regarding the determination of the linear range, this can be evaluated as:

$$(a_x^2 + a_y^2) < a_{thre} \, \mu \, g \tag{3}$$

where a_{thre} is a predetermined constant value (e.g., 0.5). On the other hand, when in nonlinear region, the control influence coefficients need to be determined. Those can be related to cornering stiffness as it describes the sensitivity of tyre forces to changes in tyre slip angle. Lastly, with the knowledge of control authority (maximum change in forces and moments) and control influence coefficients, the decision of which subsystem should be activated depends on factors like (obtrusiveness of the system to the driver, quickness of response, desired control correction, available control authority and magnitude of the influence coefficients). If, based on control authority, any system can be activated, the one with the least degree of obtrusiveness and the quickest response will be chosen. In the same period, other patents have been published by Delphi [72] where the coordinated control of brake and steering subsystem is investigated in slip coefficient surface, along with research article on the influence of each active control system (4WS, 4WD, TCS, ABS, ASS) on yaw and lateral motion in both linear a nonlinear vehicle conditions [71]. Based on similar principles of force control, the Toyota Vehicle Dynamics Integrated Management (VDIM) [73] was presented to coordinate ABS, TCS and ESP. The concept applies to both emergency and normal situations, using the brake system as the only actuator. This can be realized through a hierarchical structure, where: the first layer evaluates the target F_x,F_y,M_z based on the driver's steering input, throttle and brake; the second layer distributes the force to each wheel using a nonlinear optimizing method. The objective function involves the definition of the error between the total force and moments and their distributed values; this is all expressed as a function of k and δk, which are the slip ratio of each wheel and its variation. The other two lower layers aim at i) controlling each wheel slip rate and feeding back the maximum brake force to be applied to the upper layer, ii) the force which should be distributed to each actuator. On the same topic, Toyota released patent works with the aim of controlling the driving, braking and steering system [74].

Advances to this theory are then proposed in 2012 with the work of Ono et al. [75]. Here, an online nonlinear optimization is proposed for 4WD-4WS vehicles. The concept is to find the magnitude and direction of forces that can satisfy the total force and moment requirements while minimizing the μ rate, which is defined based on the friction circle. The efficiency of the proposed algorithm is shown when comparing the results with the general quadratic problem. Furthermore, regarding 4WD application, a great control system was introduced by Mitsubishi Motors Corporation, known as Super All Wheel Control (S-AWC) [8]. The system aimed at controlling Active Center Differential (ACD), Active Yaw Control (AYC), Active Stability Control (ASC) and ABS by evaluating the yaw moment using yaw rate feedback control and then distributing it to each wheel. The predictability of handling operations, along with a high margin of performance, both require the vehicle motion to match the driver's steering command. This can be done by evaluating the target yaw rate and then its error can be compared to the actual value measured from on-board sensor. However, there exist different chassis systems that can generate a corrective yaw moment able to drive the yaw rate to its target values, they include: steering angle control, roll stiffness distribution, longitudinal torque distribution, lateral torque difference and lateral braking control. Each of them can exploit benefits depending on the vehicle's working condition (e.g., steering angle control is beneficial in linear range). A combination of them is proposed with the S-AWC, including: lateral torque vectoring to rear wheels (AYC), and lateral braking control (ASC). Once the value of the total yaw moment is determined, the driving condition is identified (acceleration/braking/cornering). Therefore, the individual contribution of each system to the total yaw moment can be calculated. However, yaw rate feedback control algorithms require tedious calibration and when the control system is activated, the driver receives an unnatural feeling. In 2010, Bosch Engineering [76] introduced the Integrated Vehicle Dynamics control (IVC), which showed the feasibility of a new concept of feed-forward controllers. The idea is to treat the vehicle and driver as one system and increase its performance. Physical vehicle parameters are the desired values and a feed-forward methodology is applied, which consisted of a mathematical model of the actual vehicle and an inverted model of the desired vehicle. As the driver inputs (steering angle) are fed into the control loop, this provides the impression of a passive vehicle with modified physical parameters. The allocation of controller output to various actuators is performed within the inverted model. The calibration phase requires the assessment of vehicle behaviour with respect to changes in vehicle physical parameters (cornering stiffness, grip, …). This process is simplified by a correlation analysis between lateral dynamics impressions (agility, steering effort, balance and yaw damping) and IVC's internal physical vehicle parameters.

Moreover, it is necessary to introduce the work of Denso [77], which paved the road towards integrated control systems through a supervisor "managing" ECU, which is able to communicate with a plurality of subsystems and execute abnormality detection. This helps to highlight the necessary hardware development that originates from integrated vehicle control solutions. On the same topic, the patent published by Ford [78] proposed an integrated sensing system driven by measurements from sensors equipped on the vehicle. The sensing algorithm includes sensor signal compensation, plausibility check, vehicle attitude determination, vehicle parameter determination, force and loading determination, road profile and diver intention identification. Moreover, the necessity of a system-level ECU to supervise the different control functions from various sub-systems (ECUs) is stated. These latter will include supplier's partition, OEM's partition and the required interfaces. Furthermore, the importance of a lateral sensing system is also investigated in 2012 with the patent of Brown [79], which aims at providing information to conduct integrated stability control. The involved subsystems are yaw stability control, roll stability control, lateral stability control, ABS and TCS. However, the patent aims at increasing the effectiveness of standard ESP when the vehicle is driving closely to instability on a medium-sized bank road, leveraging the knowledge from the sensed variables (lateral velocity, sideslip angle). Along with instability, the issue of driving effectively and the related need for reduction of fuel emission, led Hitachi to invest in control solutions able to coordinate steering wheel and brake commands. The technique is known as G-Vectoring [80], [81] and it is based upon a correlation analysis on expert drivers' behaviour which showed a strong relationship between a_x and the lateral jerk $\dot{a}_y$. From the steering wheel position, the vehicle lateral jerk is determined and then the target longitudinal acceleration can be obtained as:

$$a_x = -C_{xy}\,\dot{a}_y \tag{4}$$

where C_{xy} is a proportional coefficient. Hitachi Group has also been working towards vehicle electronic control units for vehicles with increasing automation and connection [82]. As previously depicted, they stated the importance of a centralized unit whose role is to coordinate (supervisory approach) sub-systems: chassis domain (suspension/brakes), powertrain domain (motor/inverter/battery) and AD/ADAS domain (sensors/c2x). The integrated control field also received great attention from companies not directly related to the automotive market, as Apple testifies. They developed/bought various patents related to vehicle control, including the one [83] in 2019, where an integrated centralized control system was proposed. The structure included: a vehicle intelligence unit, environment information, state estimation, capability envelope, vehicle motion control unit, integrated chassis control system, allocator and a low-level control unit (along with specific actuators, e.g., suspension/steering/drive and brake). The vehicle intelligence control unit determines the motion plan for the vehicle (intended speed and path), the motion plan is based on traffic, lane use, and sensor data to describe a route towards the destination. The capability envelope describes limitations of the vehicle and its dynamic limitations; its development involves describing the limits of each component (suspension/steering/braking/propulsion) as the maximum feasible acceleration. The vehicle motion control unit receives the motion plan and generates information that describes the desired chassis-level motion (reference acceleration). One model that can be employed is the suboptimal LQR with pole placement and MPC [83]. The integrated chassis control system includes the allocator and the low-level control and it is used to coordinate the effort across the available actuators. This, however, is not directly dependent on the specific type of actuator and it is fault tolerant. The allocator compares several control strategies and may consider factors such as the actuator's saturation or the minimization of energy consumption to determine force and angles for each tyre that minimize the difference between $F_{feasible}$ and F_{des}. The low-level control unit then converts the allocator's outputs into inputs required by the actuators. Furthermore, in 2021, other advances in stability control within particular driving scenarios have been proposed by Hyundai and KIA with the coordination of ESP and AFS [84]. The aim was to deal with inclined road conditions with a first target yaw rate identification (based on steering angle and vehicle speed) and correcting it with a target yaw moment. That will be expressed as front wheel steering angle and biased braking torque. The patent underlines the importance of knowing the vertical acceleration values to identify whether the vehicle is travelling on an inclined road, which can be obtained through controlled suspension systems. Regarding the sensing environment, its necessity has already been depicted; however, the more understanding leads to more controllability, especially when describing the tyre-road interaction.

Recently, Pirelli and Bosch [85] have been working towards the development of high performance sensorized tyres which could gather further information over ordinary sensors. They are referred to as Cyber Tyres and can provide crucial knowledge regarding contact forces, friction conditions, inflation pressure, and road conditions (presence of water layer). This can be regarded as a valid substitution with respect to state observers; however, their industrial diffusion is still limited due to high production costs and the need for integration within standard electronic control units. Furthermore, other major players have not been included in this dissemination as there is still a lack of scientific details; however, they can be found in Table 3. The surveyed solutions consistently chase a trade-off between functional integration, complexity and fault-tolerance property shaping commercial products: hardware computational ceilings on standard ECUs favour simpler controllers over NMPC/ML inference; sensor cost–reliability trade-offs constrain state estimation robustness; calibration scalability across variants drives engineering effort; validation burden scales non-linearly with integration level, favouring modular interfaces despite sub-optimal global performance; and supply-chain/IP protection steers proprietary integration over transparent global optimization. Each industrial system category in Figure 4 faces distinct engineering realities, including actuator availability and vehicle morphology, that offer concrete selection criteria beyond abstract performance metrics, further constraining practical implementation, as well as it underscores that architecture selection should align with vehicle segment, target market, regulatory context, and OEM strategy:

- ML-based centralized systems: require high-end ECUs with significant computational capacity, extensive and redundant sensor suites for fault tolerance under degraded conditions, and advanced AI/ML expertise for development and validation; trade-off: high adaptability and peak performance versus elevated complexity, cost, and certification burden;
- model-based integrated systems: balance integration and accuracy yet depend strongly on physical-model fidelity and sensor precision, demanding wide-ranging calibration across variants and real-time compromises between model fidelity and execution time; trade-off: proven methodology and solid performance versus calibration intensity and residual model uncertainty across the operating envelope;
- stable conventional systems: leverage mature hardware/software stacks, standardized ECUs, established calibration workflows, and conservative performance margins that favour safety and reduce development risk; trade-off: reliability and predictability versus limited adaptability to novel scenarios, lower performance ceiling, and continued reliance on manual calibration;
- coordination-based systems: orchestrate multiple ECUs over in-vehicle networks, facing actuator synchronization demands, latency effects on closed-loop performance, conflict resolution across controllers, and priority handling under concurrent requests; trade-off: broad functional coverage versus synchronization complexity and latency constraints;
- pioneering modular systems: compose independent subsystems with basic coordination logic, enabling cost-effective deployments and robust operation with minimal integration overhead; trade-off: simplicity and favourable cost profile versus limited cross-subsystem synergies and modest performance gains.

From a perspective point of view, all the investigated industrial applications can be formalized in three major research directions: vehicle control structures, vehicle sensing systems and vehicle electronic control units. Specifically regarding the structures, they are normally divided into various layers, each of them has a specific purpose and can receive information from sensors or the sensing system (observer/state estimators). Moreover, the determination of the working condition is usually performed based on the feedback between a measured and a target value and it is used to trigger the activation of the controllers or to switch between different modes. It is evident, however, how control algorithms are generally based on common PID, nonlinear controllers with feedback terms, LQR; this being mainly due to limitations in hardware capabilities when employing more sophisticated control methods.

IV. VEHICLE MORPHOLOGY AND ACTUATORS AVAILABILITY

As previously highlighted, actuators play a crucial role in integrated control structures: while on one hand they represent the fundamental link between control actions and their practical execution, on the other one, the multiplicity of available actuators can generate redundancy in the control problem statement. To this purpose, the allocation problem [86], in the context of integrated control, has been methodologically reviewed in [6] and explored by many researchers [7], [87], [88]. The proposed manuscript paper aims at addressing the problem from yet another point of view: given a set of actuators usually adopted within the chosen commercial vehicle solution, is there a way to objectivize the criteria to determine which control structure should be adopted for that specific configuration? What does the current state-of-art offer towards solving the applied integrated control problem, specifically focusing the investigation on methodologies and needs of non-didactic solutions?

As of today, an extensive spectrum of vehicle morphologies and corresponding actuator sets complicates the classification and clustering task addressed in this section. The authors' investigation seeks to distil this diversity into a minimal ensemble of representative configurations that encompass the market's most prevalent solutions, thereby guiding researchers and industry practitioners.

After a detailed and rigorous analysis, three principal criteria were defined for grouping vehicle morphologies: a) traction type: front-wheel drive (FWD), rear-wheel drive (RWD), all-wheel drive (AWD), four-wheel drive (4WD); b) number of motors: 1, 2, 3, or 4; c) powertrain architecture: internal combustion engine (ICE), electric vehicle (EV), or hybrid (HEV/MHEV). Applying these criteria to the

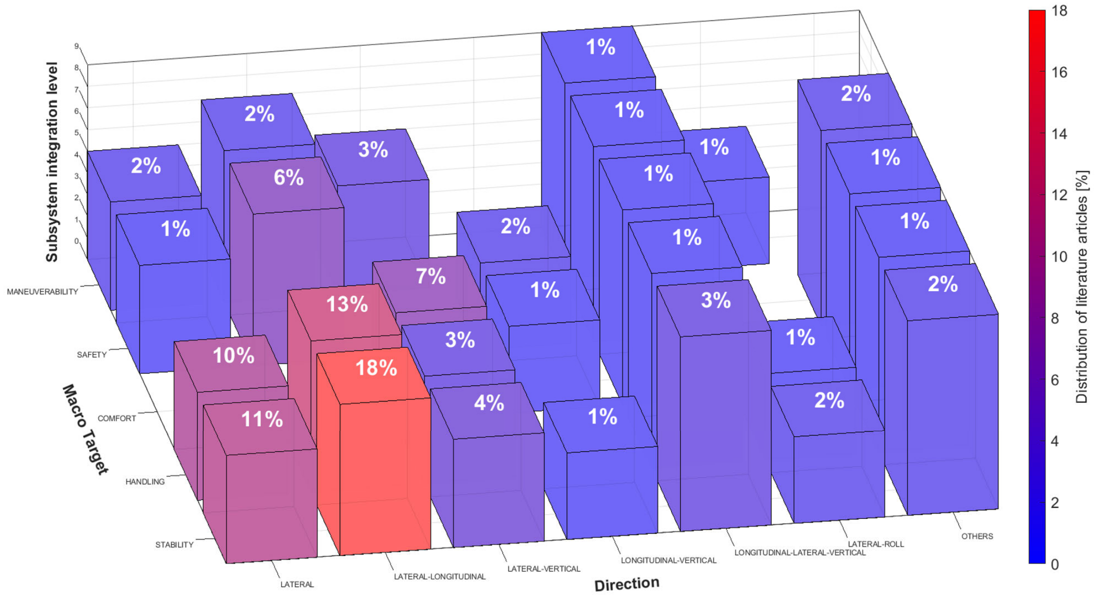


FIGURE 3. Control direction and macro target classification of articles on IVDC, "others" include: Vertical/Roll, Vertical/Roll/Pitch, Lateral/Longitudinal/Camber. The colormap highlights articles' percentage distribution (e.g., adoption rate) while the z-axis refers to the level of subsystem integration.

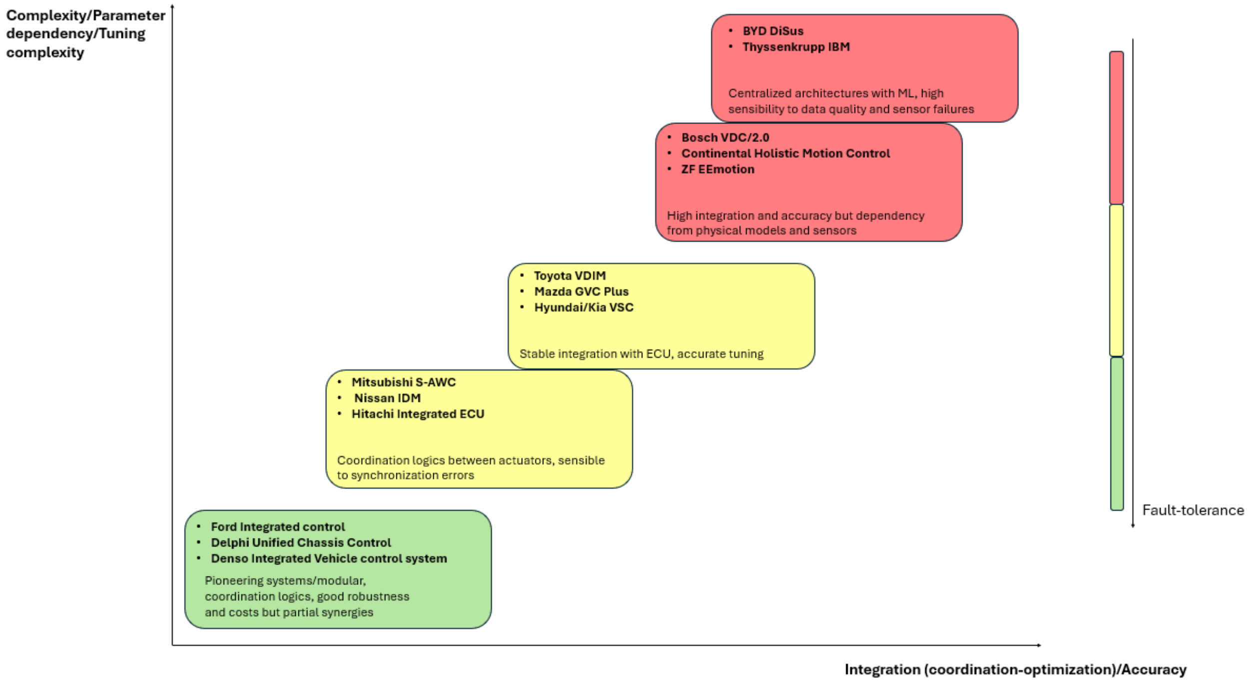


FIGURE 4. Qualitative engineering trade-off map of industrial vehicle integrated control systems. Data points and clusters are derived from the industrial systems listed in Table 3 and positioned according to publicly available technical descriptions and TRL maturity.

market-available solutions yields seven distinct categories: a) ICE FWD; b) ICE RWD; c) ICE 4WD; d) EV 1 (single motor, front or rear); e) EV 2 (one motor front + one motor rear); f) EV 3 (one motor front + two motors rear); g) EV 4 (four motors). Using this framework, to validate this minimal taxonomy, three representative vehicles (A, B, and C) were selected for each category; the inclusion criteria required that each vehicle must be currently available and belong to a comparable price segment. Within each morphology, the authors have catalogued the actuators most commonly employed; the results appear in Table 5 (columns left blank correspond to premium, low-adoption actuators excluded from our scope in favour of solutions with broad market penetration).

TABLE 3. Industrial applications of vehicle integrated control. TRL (Technology Readiness Level): Green = commercial/real vehicle; Yellow = prototype/concept/pre-production; Red = proof-of-concept/demo/early stage.

Year	Company / OEM	System/Technology	TRL	Description
1995	Bosch	VDC (Vehicle Dynamics Control)	🟩 SLS AMG Electric Drive (2013)	ABS, TCS, ESP
2002	Delphi	Unified chassis control	🟩 Cadillac Seville and Deville	ABS, ESP, TCS, EPS
2004	Toyota	VDIM (Vehicle Dynamics Integrated Management)	🟩 Crown Majesta - Lexus	VSC, ABS, TCS, EPS
2004	Toyota	Vehicle Integrated Control System	🟩	Centralised control of powertrain, brakes, steering, transmission, suspension
2005	Mitsubishi	S-AWC (Super All Wheel Control)	🟩 Lancer Evolution X (2007)	4WD, ACD, TV, ESP, ABS
2006	DENSO	Integrated vehicle control system	🟩	System to coordinate individual ECUs through a managing ECU
2009	FORD	Integrated vehicle control	🟩	Sensing system, actuators by various ECUs, coordination of DYC, ESP, RSC (roll stability control)
2012	FORD	Integrated control system for stability	🟨	Integrated sensing system to determine lateral velocity
2016	Mazda	G-Vectoring Control (GVC)	🟩 Mazda Axela - Mazda CX-3	Motor torque modulation
2016	Nissan	Integrated Dynamic-control Module (IDM)	🟩	ABS, TCS, VDC, Active Trace Control, Active Ride Control, motor torque, EPS, yaw control
2018	Mazda	GVC Plus	🟩 Mazda CX-5	TCS, ESP, motor torque
2018	DENSO, AISIN, ADVICS, JTEKT	Integrated ECU	🟩	Joint venture to develop software for integrated ECU: brake, steering and sensor ECU
2018	Hitachi	Integrated ECU	🟩	Target trajectory by supervisory controller, acts on each vehicle motion, fault-tolerant
2019	Apple	Integrated Chassis Control	🟨	Steering, braking and suspension coordination for stability and safety
2020	Bosch	Vehicle Dynamics Control 2.0	🟩 Mazda Roadster NR-A	ASS, powertrain, steer-by-wire, ESP
2020	Audi	Electronic Chassis Platform	🟩 Suv E-TRON	Traction, TV, ESP, suspension, powertrain
2021	Hyundai/KIA	Vehicle stability control system	🟨	Cooperative control of AFS and ESP
2021	Continental	Holistic Motion Control Software	🟩	Centralized solution for steering, brake, powertrain and suspension
2021	Pirelli	Bosch Cyber Tyre	🟨	Smart tyres with sensors that provide real-time data to vehicle control systems
2022	Hitachi	Dynamics planning/G-Vectoring/Vehicle attitude/Vibration suppression control	🟨	Techniques for ride comfort, safety
2023	BYD	DiSus Intelligent Body Control	🟩 Yangwang U8 - DENZA N7	Damping, air and hydraulic body control for longitudinal, lateral and vertical motion
2024	ZF	Infineon EEmotion	🟥	Software-based chassis control with AI; integrating steering, braking, suspension
2024	Thyssenkrupp + IBM	IVDC with AI	🟥	Integrated control unit for AVs: braking, damping and powertrain
2024	ZF + Foxconn	x-by-wire IVDC	🟨	Joint venture for high-performance chassis integration
2024	TDK	Sensors and Controllers	🟨	Inertial sensors, embedded motor controllers, navigation support
2024	BYD	iTAC (Intelligent Torque Adaption Control)	🟩 BYD Seal Performance AWD	Torque adaptation control: traction, handling, stability
2024	BYD	Integrated Vehicle Intelligence Strategy	🟨	Perception-driven decision system for vehicle stability and comfort
2024	Honda	Integrated Dynamics Control	🟩	Transmission, battery, EPS, dampers, brakes, AWD and vehicle stability assist
2025	BMW	Heart of Joy ECU	🟨	Centralized ECU for torque distribution and vehicle dynamics. Works with Dynamic Performance Control
2025	Geely	AI Digital Chassis / G-Pilot	🟨	Unified driving platform for chassis, powertrain and cabin integration in AVs

The authors' analysis reveals that OEMs consistently deploy near-identical actuator suites for a given morphology, including: 4WS, 4WD, ASS/SAS, ABS, TCS, DYC, ESP, AFS, ARS, DB, EPS, BTD, Steer-by-Wire, CDC, ADAS, Drive-by-Wire, ARC, and TV. Notably: 4WS is confined to high-end vehicles, irrespective of powertrain; AFS predominates in premium ICE 4WD and in EV 2–4 architectures; ARC appears in ICE RWD as well as in EV 2 and EV 3.

The selection of one actuator set over alternatives hinges on several factors, such as cost and system complexity, desired dynamic performance, target segment and customer expectations, compliance with safety and regulatory standards:

- considering type of traction and number of motors: the FWD ICE vehicle does not require TV or AD on the rear axle, while the actuators could be beneficial for 4WD solutions. Moreover, EV 4 does not need DB or AD because it can distribute torque in an easier way through its motors. Furthermore, systems like DYC found suitable applications in EV 2,3,4 as the number of motors directly influences the transmitted torque and the possibility to control it;
- considering performance-needs and cost-market target: systems like TV, ARC and AD are widely employed in high-end vehicles rather than mass/passenger ones as the latter do not require to meet specific performance needs. It is possible to observe that functions like BTD or DB are included only in vehicle "A" (ICE, FWD) as a consequence of "A" being oriented to a more "premium" portion of the market, thus not aiming at providing the best quality-price deal. Furthermore, a specific set of actuators can represent the brand's signature to establish unique value propositions (brand identity) and develop competitive advantages.
- considering weight and efficiency: systems like ARC and TV add weight, therefore decreasing the efficiency and increasing consumption, ultimately being not preferred in configurations (e.g., EV 1) where the main objective is to maximize the autonomy.
- considering regulations: each vehicle is designed to be widely spread in some geographical areas and they all have their own regulations; however, there are some mandatory active controls (mainly oriented towards safety), such as ABS and ESP which are always included.

It is important to stress that these are general guidelines, not rigid rules. For example, on an EV 4 platform, dynamic braking (DB) may be activated in specific scenarios (as tight turns or slippery surfaces), while in off-road use, it can function as a locked differential. Moreover, adding a dedicated actuator can introduce redundancy and elevate overall safety by building on existing systems such as ABS and ESP.

TABLE 4. Literature works classified by the type/set of actuators employed.

Actuators	Related works	Macro-target
AFS+DYC	[90] [89] [91] [92] [93] [94] [95] [96] [97] [98] [99]	Stability / Handling
EPS+ASS/SAS	[100] [101] [102] [103] [104] [105]	Comfort / Manoeuvrability
4WS+4WD	[106] [107] [108] [75] [109] [110] [111] [112] [113] [114] [115] [37] [116] [117]	Handling / Stability / Manoeuvrability
ABS+ASS	[118] [119] [120] [121] [122]	Safety / Comfort
ESP+AFS	[31] [123] [124] [125] [126]	Stability / Handling
4WS+DYC	[127] [128] [129] [130]	Stability / Manoeuvrability
AFS+ASS	[131] [132] [33]	Comfort / Handling
ASS+ESP	[133] [134]	Handling / Stability / Comfort
AFS+DB	[135] [136] [137] [138]	Safety / Stability
4WD+DYC	[139] [140]	Safety / Stability
AFS+AD	[141] [142]	Handling / Stability
EPS+ABS	[143]	Stability / Manoeuvrability
DB+ASS	[144] [145] [146]	Stability
TV+ESP	[147] [148]	Stability / Handling
EPS+TCS+4WD	[149]	Stability / Longitudinal performance
AFS+4WD	[150] [151]	Handling / Stability
AFS+ABS	[152]	Stability / Safety
ABS+ARS	[153]	Safety / Handling
4WS+ASS	[154]	Handling / Comfort
DS+4WD	[155]	Stability / Handling
ESP+CDC	[156]	Safety / Stability
AFS+ARS	[157]	Handling / Stability
ABS+SAS	[158]	Comfort / Safety
ABS+ESP	[159] [160]	Stability / Safety
4WS+ASS	[161]	Handling / Stability
4WS+ARC	[162]	Handling / Stability
EPS+ESP	[163]	Safety
ARS+ESP	[164]	Handling / Stability
DYC+DB	[165]	Stability / Safety
4WD+AFS+DYC	[166] [167] [168] [169] [170] [171] [172]	Handling / Stability
AFS+DYC+ASS	[173] [174]	Stability / Handling / Comfort
AFS+AD+ARC	[175]	Handling / Manoeuvrability
ABS+ESP+4WS	[176]	Stability / Manoeuvrability
ASS+ABS+AFS	[177]	Comfort / Stability
AFS+DB+ASS	[178]	Stability
4WD+ESP+AFS	[179]	Stability / Manoeuvrability
4WD+4WS+CAMBER	[180]	Handling / Stability
ESP+ARS+ASS	[181]	Comfort / Manoeuvrability / Stability
AFS+DYC+ACTIVE TILT SYSTEMS	[182]	Safety / Stability
AFS+ABS+ARC	[183]	Stability / Safety
DB+ESP+SAS	[184]	Stability / Safety
4WS+4WD+DYC	[185]	Handling / Stability
TWO WHEEL INDEPENDENT+AFS+DS	[186]	Handling / Stability
4WD+DB+AFS	[187]	Handling / Stability / Safety
AFS+ESP+ABS	[188]	Stability / Safety
4WS+4WD+ASS	[189]	Handling / Comfort
4WS+VDC+ARC	[190]	Comfort / Handling / Stability
4WD+ARS+DYC	[191]	Stability / Safety / Handling
AFS+ABS+AD	[192]	Stability / Safety
ESP+AFS+CDC	[193]	Manoeuvrability / Stability
4WS+ASS+ABS+TCS	[194] [10]	Handling / Comfort Safety
AFS+ASS+ESP+VTD	[195]	Handling
ASS+AFS+ABS+DB	[196]	Safety / Comfort / Stability
4WD+DDAS+VSC+ASR	[197]	Handling / Stability
AAC+ARS+TV+ASS	[198]	Comfort / Stability / Safety
AD+DYC+ESP+ABS	[8]	Handling / Safety
AFS+ARS+4WD+DB+ABS+ASR	[199]	Handling / Stability / Safety
TV+DB+AFS+ARS+CAMBER	[200]	Stability / Safety

Table 4, concerning the relative distribution of the research work based on the type of actuators employed within the studies, can also unveil some interesting concepts. First of all, the sorting methods adopted in this table highlight that the majority of works deal with the adoption of AFS and its combination with DYC or DYC and 4WD. The rationale behind that can be found in the possibility of covering all the domain of lateral acceleration as the AFS application domain is limited to linear vehicle handling region [89], while DYC guarantees good performance in critical non-linear situations; therefore, from the control point of view, the two systems could mutually act by hiding their relative flaws.

It is also interesting to observe that as highlighted by other literature reviews [19], the number of studies on the integration of three or more subsystems/actuators is indeed lower compared to applications of two subsystems (it is worth mentioning that, as presented in Table 5, active systems involving suspension control have been associated under the ASS/SAS category for simplification reasons, independently from the particular mechanisms adopted (e.g. hydro-pneumatic suspension, etc). On the other hand, although there is considerable interest in developing control systems for 4WS+4WD vehicles, existing studies lack a systematic approach that incorporates a realistic set of actuators in

TABLE 5. Common actuators for each vehicle category, three vehicles (A,B,C) were chosen.

	ICE, FWD	ICE, RWD	ICE, 4WD	EV 1	EV 2	EV 3	EV 4
4WS							
4WD			A B C		A B C	A B C	A B
ASS/SAS		B	A		A B	A B	A
ABS	A B C	A B C	A B C	A B C	A B C	A B C	A B C
TCS	A B C	A B C	A B C	A B C	A B C	A B C	A B C
DYC		B		B	A B	A B	A B
ESP/ESC	A B C	A B C	A B C	A B C	A B C	A B C	A B C
AFS							
ARS							
DB	A	A B	A B	B	A B	A B	A B
EPS	A C	A B C	A B C	A B C	A B C	A B C	A B C
BTD	A	A B	A B	A B	A B	A B	A B
SBW							
CDC		B	A		A	A	A
AD		A B	A				
DBW	C	B C	C	A B C	A B C	A B C	A B C
ARC							
TV	B	A	AB		A	AB	A

conventional vehicles, that shortfall likely explains OEMs' growing focus on modern automotive platforms [201], [202].

This section investigates key actuator configurations used in modern vehicles. Two main categories are examined: the minimum mandatory safety set and advanced multi-actuator platforms. Each section presents the typical components, combinations of interest, and control-architecture approaches.

A. MINIMUM CONFIGURATION

This category covers the smallest set of active safety systems found in nearly all road vehicles and represents the baseline actuators mandated or commonly installed for safety and drivability, as ABS, ASR, ESP and EPS. The study focuses on paired and triplet combinations to assess interaction, sensor inputs and control logic requirements, where modern stability control (ESP) inherently depends on ABS and ASR functions.

1) ESP+ABS/ASR

An initial general workflow adopted for the stand alone integration of these subsystems is presented in [160]; the introduction of a control decision table allows for defining the domain of actions in which each subsystem has to run. The authors divided the normal straight driving from the steering driving and subsequently the braking from the driving conditions. The former is associated with ABS while the latter with ASR (anti-slip regulation), which is typically designed to avoid sliding during acceleration manoeuvrers. This work distinguished between stable and unstable regions, the latter being assigned to ESP; however, they do not clarify which is the variable/set of variables used to define the system's stability. Indeed, the importance of having ESP together with ABS/ASR has been highlighted through results simulations, which portrayed smaller slip angles and better yaw response. It also becomes noticeable how those conditions (braking/accelerating and cornering/straight driving) cannot fully represent the multiplicity of scenarios, thus ignoring the emergency-related role of these active systems. Complex road profiles and friction conditions have been investigated by [159]. The choice of a fuzzy logic control for the two systems has been motivated by its robustness and simplicity for a wide range of vehicles, including on and off-road ones. Firstly, the authors evaluated optimal wheel slip values for several road conditions. The two active systems have been designed by using different sets of inputs (friction coefficient and slip value for ABS; yaw rate and driver's steering angle for ESP) and the brake pressure as output. The ABS/ESP activation is associated with the braking pedal and does not function below a certain critical speed; they work together as the value of braking pressure obtained by the ESP controller alone is subtracted from the pressure generated from the ABS control (Fig.5).

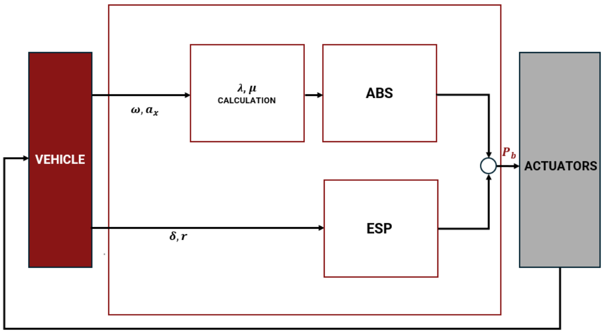


FIGURE 5. Workflow of ABS+ESP control logics, employing fuzzy logic controller, adapted from [159].

2) EPS+ESP

The choice of integrating these two subsystems originates from the increasing availability of lane departure avoidance systems in modern vehicles. The authors of [163] proposed the integration of ESP, commonly involved in normal driving scenarios, with ESP systems as they provide both steering and braking control when reaching vehicle's handling limits. This work, however, underlined the mutual interference of the driver's control and its control actions on conventional machine active controllers. The conflict, originating from the steering angle applied by the driver, known as man-machine cooperative control, can be translated as a disturbance input and must be addressed while designing such a control logic. The coordination between steering and braking is achieved through an upper monitoring layer.

3) EPS+ABS

A two-level hierarchical control architecture is developed in [143], the upper level monitors the driver's intentions and the current vehicle conditions, including the torque applied to the steering wheel, the vehicle speed, the wheel speed and the yaw rate (Fig.6). The objective is to define the control commands (change of assist torque ΔT_m and braking torque ΔT_b to be sent to the lower-layer individual controllers). The working domain has been predefined, as the ESP system is set to be active between 0 to 40 km/h, whereas the ABS is employed when the vehicle velocity reaches

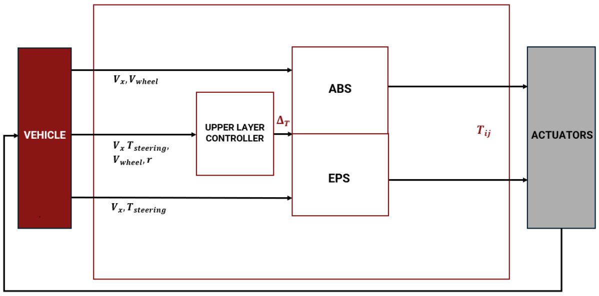


FIGURE 6. **Hierarchical structure of ABS+EPS control logics, adapted from [143].**

20km/h or higher. The overlapping domain is therefore between 20 to 40km/h and has been investigated through slip-adhesion curves. An overall performance index named J, whose definition is:

$$J = \sqrt{\frac{W_1 J_1^2 + W_2 J_2^2 + W_3 J_3^2}{W_1 + W_2 + W_3}} \tag{5}$$

where J_1, J_2, J_3 are the variances of the driver's steering torque T_c, while W_i are the weighting parameters. This index is used to coordinate the choice of EPS or ABS in the overlapping area. In that case, the controller will aim at minimising the overall performance index.

B. ADVANCED CONFIGURATION

Advanced platforms increasingly feature multi-wheel drive and multiple electric or internal-combustion actuators: to this category belong ICE 4WD, EV 2,3,4, as they commonly employ four-wheel-drive systems. However, comprehensive control solutions have yet to converge on standardized architectures, so research to date has focused primarily on subsystem integration and multi-layered control frameworks. Furthermore, as we pave the way toward fully autonomous vehicles—characterized by both intra-vehicle and V2X interconnectivity, the above lack of unified standards, coupled with the gradual escalation of ADAS toward higher automation levels, becomes more evident, yielding a proliferation of prototype implementations. Some of these prototypes may be sufficiently mature for near-term commercial deployment, yet they often lack the long-term adaptability required to accommodate the ever-growing complexity of technologies, use-case requirements, and regulatory demands inherent in next-generation mobility systems.

Most advanced studies adopt a multi-layer control hierarchy to manage competing objectives such as lateral stability, rollover prevention, and energy efficiency. An example of this application for an EV with front and rear motors equipped with independent braking modules is presented in [203]: supervisory controller selects control model, defines admissible control regions and sets desired dynamic targets; upper-layer controller allocates total traction force and determines required yaw moment; lower-level controller translates commands into individual actuator inputs (Fig. 7).

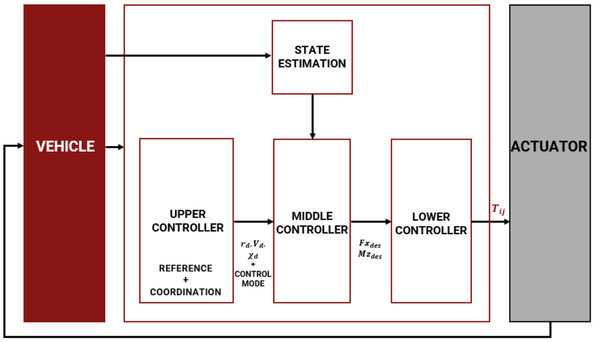


FIGURE 7. **4WD vehicles control structure for rollover mitigation and lateral stability control, adapted from [203].**

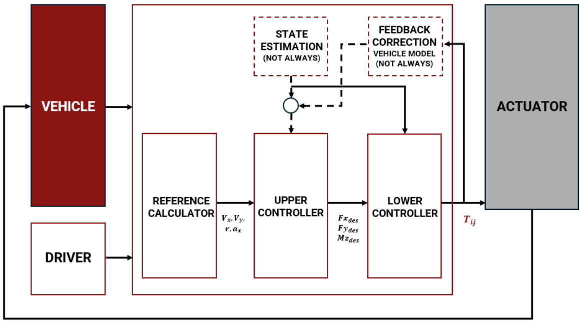


FIGURE 8. **4WD, 2 layers control structure, adapted from [204], [205].**

A specialisation of the previous structure is the two-level control system presented in [204], where the upper layer computes the longitudinal, lateral force and the yaw moment to track the desired dynamics based on the SMC, while the lower layer evaluates the driving/braking torque for each wheel (Fig. 8). Another similar example is described in [205]. Although the two layers have been assigned to the same objectives as before, the control algorithm has changed. It utilizes a Particle Swarm Optimization (PSO) based Nonlinear Model Predictive Control for the upper layer and then the same PSO method for torque allocation and braking pressure regulation in the lower half of the structure (Fig.8).

Advanced configurations employing four-wheel-drive systems can be further classified by their integration with additional subsystems, as wheel-steering controllers, stability controllers, and vertical-motion controllers, as follows:

1) WHEEL STEERING CONTROLLERS

a: EPS

Due to the nature of EPS and TCS being widely adopted active systems, their coordination will be briefly addressed through a hierarchical two-level structure, whose upper layer will be assigned to managing the coupled effects of the two subsystems [149]. It is often the case where the two subsystems (located in the second layer) are not designed based on their mutual integration; instead, there is the introduction of specific correction terms. For the EPS, when accelerating and steering simultaneously, the current of the assist motor has to be corrected to warn the driver (increased wheel steering torque) and decrease the possibility of higher steering angles (which directly relate to unstable conditions):

$$I_a^* = KI_a \tag{6}$$

where I_a^* is the corrected value of the current, while K is the weighting factor of coordinated control. The same concept is applied to TCS, where the target slip ratio becomes a function of a corrective parameter which is directly dependent on the steering shaft and road adhesion coefficient.

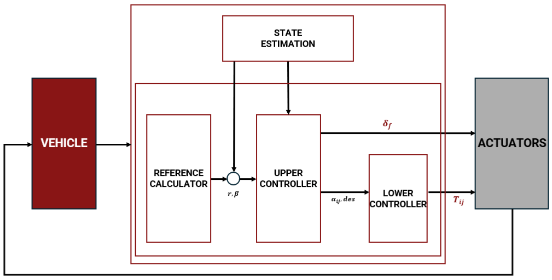


FIGURE 9. Control structure of 4WD+AFS vehicle, adapted from [150].

b: AFS

Wu et al. [150] proposed a hierarchical integrated control based on two levels for AFS and four wheel braking torque control (Fig. 9). The first layer is a robust model matching controller that optimizes an active front wheel steering angle compensation and a desired yaw moment control, while evaluating the reference wheel slip for the target wheel according to the desired yaw moment. The wheel slip angle will be the input for the second layer, which is based on a moving SMC that acts by tracking the references and generating the wheel braking torques.

In [186], a two-wheel independent driven and steered AGV is controlled through a coordination strategy based on path tracking objective. Three levels can be identified (Fig. 10): a first path following controller based on MPC that evaluates the steering angle of the front-wheel (AFS); the differential steering controller and a coordination layer that allocates the output weight coefficient contributing between steering angle and driving torque output.

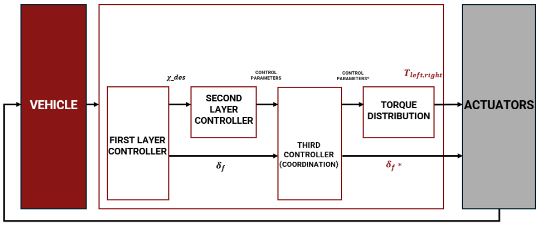


FIGURE 10. Control structure of 2WD+AFS vehicle, adapted from [186].

Additionally, a newer frontier of control actuators includes electrically guided systems such as SBW, the work of [151] has been added to this paragraph because it deals with front wheel steering angle control through SBW actuator. The two-level architecture has been chosen; the first one being dedicated to quantify global control variables F_x,F_y,M_z based on input-output linearisation, while the lower layer distributes the total forces among the six degrees of actuation (no rear wheel steering angles are controllable).

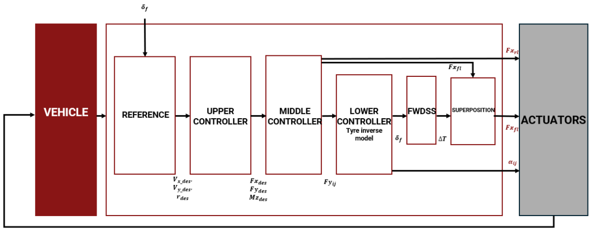


FIGURE 11. Control structure of 4WD+DS, adapted from [155].

c: DS

The front wheel steering command can also be realized through the differential driving torque between the left and right front wheels. For that purpose, [155] developed a hierarchical three-level controller based on an upper layer which evaluates the resultant forces and torques through a sliding mode controller. The outputs are, then, decomposed into longitudinal and lateral forces of four wheels by quadratic programming method by the middle controller, lastly the lower controller converts the lateral forces of the four wheels into the front wheel steering angle and the tyre sideslip angles through an inverse tyre model. Indeed, the steering angle will be, then, fed into the front wheel differential steering system model to obtain the differential driving torque ΔT. The complete scheme is presented in Fig. 11.

Moreover, the adoption of a differential drive assist steering system (also known as DDAS) can, ultimately, be able to substitute the traditional power assist steering actuators (EPS) while reducing hardware cost and required space. The work of [197] is indeed one of the most complete on the topic, by proposing a hierarchical coordinated control strategy based on the stability analysis for the integration of 4WD, DDAS, VSC and ASR. The presented structure is composed of four levels: the parameter estimation layer, the control region division layer, the coordination layer and the control allocation. While the first layer is devoted to estimate sideslip angle, speed of the vehicle and adhesion coefficient, the control division layer (as previously mentioned) determines the vehicle stability boundary. The latter two layers include the DDAS controller and yaw moment controller based on the idea that in the overlapping region the yaw moment produced by the DDAS may increase the risk of instability. The VSC works on the rear wheels while the DDAS works on the front and simultaneously adjust the weight coefficient distribution between the two subsystems. The last layer is devoted to the torque distribution controller and ASR (Fig. 12).

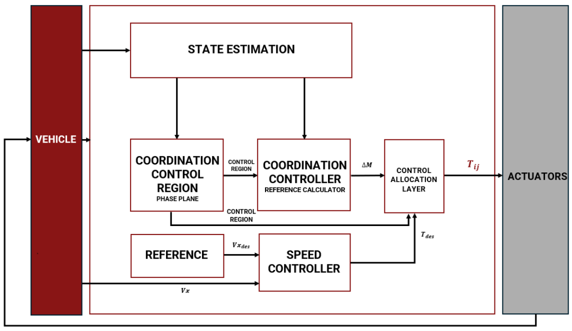


FIGURE 12. **Control structure of 4WD+DDAS+VSC+ASR, adapted from [197].**

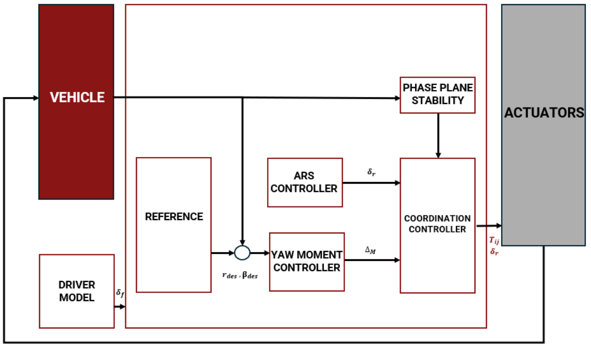


FIGURE 13. **Two layer hierarchical control structure, adapted from [112].**

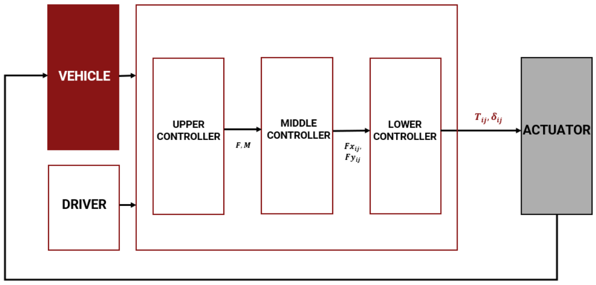


FIGURE 14. **Hierarchical structure of 4WD/4WS, adapted from [114].**

d: ARS

On the same topic, in case of active rear wheels steering and 4WD active systems, a two-level structure [112] is based on a first layer which is devoted to evaluate the desired value of yaw rate, sideslip angle and total driving force. The lower decision layer includes ARS based on Varying parameter Linear Quadratic Regulator (VLQR), a compensated yaw moment control based on FC (Fuzzy Control) and a dynamic coordination control based on phase-plane region (Fig. 13).

Within this context, other works include the coordination of two systems (ARS and ESP) through phase plane trajectory investigation [164] for 4WD vehicles. This structure can be seen as a two-layer solution where, firstly, the individual controllers determine the desired yaw moment and steering angle and then a coordination strategy is employed based on the availability of sideslip angle measurement. This latter consideration should, however, require the introduction of a state observer as the sideslip angle and its derivatives are not easy-to-measure variables.

e: 4WS

The structure not only takes advantage of a scheme where each wheel can be independently controlled, but also the steering angle of both front and rear wheels can be changed. A common choice is the hierarchical three levels (Fig. 14): the first layer calculates the target force and the moment of the vehicle and then in the second layer those are distributed to the wheels according to a specific criteria (tyre grip margin) and, in addition, a wheel control layer controls the motion of each wheel to achieve the target tyre force. [108], [114]. Those research works originate from the knowledge of the tyre grip margin $\epsilon = 1 - \frac{\sqrt{F_x^2+F_y^2}}{\mu F_z}$, from which the μ rate of each wheel can be defined as:

$$\gamma_i = 1 - \epsilon_i = \frac{\sqrt{F_{xi}^2 + F_{yi}^2}}{F_i} \tag{7}$$

where F_{xi}, F_{yi} are the longitudinal and lateral forces of the i-th wheel, F_i is the radius of the friction circle of the i-th wheel. The μ rate is controlled to become the same value for each wheel, equalizing the work load of the tyres. The second layer of the controller will have to act on the angle between the tyre force and the X-axis, named q_i, to minimize γ. Sequential Quadratic Programming (SQP) is employed on the following constraints:

$$\gamma \sum_{i=1}^{4} F_i cos(q_i) = F_0 \tag{8}$$

$$\gamma \sum_{i=1}^{4} F_i sin(q_i) = 0 \tag{9}$$

$$\gamma \sum_{i=1}^{4} F_i(-a_i cos(q_i) + b_i sin(q_i)) = M_0 \tag{10}$$

where F_0, M_0 represent the target force and moment value. The configuration of 4WD/4WS results in maximised resultant force when compared with four-wheel distributed steering control.

Furthermore, Ono et al. [75] proposed an enhanced load-distribution algorithm that minimizes the upper limit of the μ rate for each tyre, enabling the achievement of the theoretical limit of the integrated control.

On the same topic, [206] proposed a more general hierarchical five levels structure (Fig.15), the first one being dedicated to identification and estimation of parameters, the second employs a bicycle reference model to calculate the desired vehicle states, the third evaluates the forces and moment required while the last two solve the control allocation problem.

A similar hierarchical (two-level) structure is adopted in [111], [115], and [117] where a motion control (upper) layer determines the overall tracking performances (global force and moment) and then a tyre allocation layer deals with

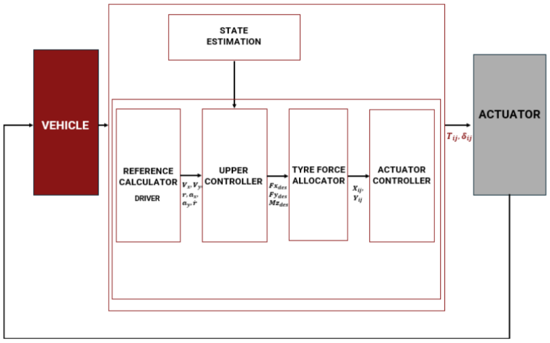


FIGURE 15. Control structure of 4WD+4WS five layers, adapted from [206].

tyre adhesive limits and calculates the individual actuator inputs (Fig. 16). The higher-level controller employs an LQR controller to obtain the desired generalized lateral force F_y and the yaw moment M_z in [111] (the longitudinal tyre force is then derived as a function of accelerator/brake pedals). The lower-level controller, instead, will aim at maximizing the grip margin during control allocation by obtaining the global minimum force point of the index function chosen. Another, more recent, example of two-layer structure is proposed by [113] where the upper layer is a trajectory tracking controller based NMPC whose outputs are the wheel deflection angle δ and the longitudinal acceleration a_x. Because of the nonlinear nature of the vehicle model, there are coupled second-order and first-order derivative terms which have been decoupled to obtain a feasible predictive model. Afterward, a lower decoupling controller is adopted to obtain the eight-dimensional control variables $u = (\delta_{ij} T_{ij})$ which represent the wheel angles and torques at the four corners.

Alternatively, an integrated control strategy can be obtained through linearization of a nonlinear vehicle model [107]. The yaw motion of the vehicle $I_z \frac{d\gamma}{dt} = a_1 F_1 - a_2 F_2$ is linearized by a nonlinear variable transformation. The input-output method [207] describes only the yaw motion, removing the lateral dynamics, which will be checked afterward. The pseudo input calculated using a linear controller is then required to transform into real inputs; a performance index is used to coordinate steering and traction control. From its minimisation and knowing the relationship between pseudo-input and real ones, the real control input can be evaluated using a steepest descent method (additional details can be found in [107]).

Moreover, the assumption of constant longitudinal velocity is widely employed when designing a 4WS controller; however, in most practical cases, the speed changes during turns, therefore vehicle longitudinal dynamics must be considered along with lateral and yaw motion. In [110], a 3 DoFs dynamic model is considered and compared to the classical 2 DoFs solution. The proposed controller is a nonlinear robust control based on the error between the desired trajectory of the system and the actual states (including vehicle longitudinal, lateral and yaw velocity). The approach supports 4WD as well as front wheel drive or rear wheel drive by adjusting a coefficient that reflects the portion of the total driving force distributed to the front and rear axles.

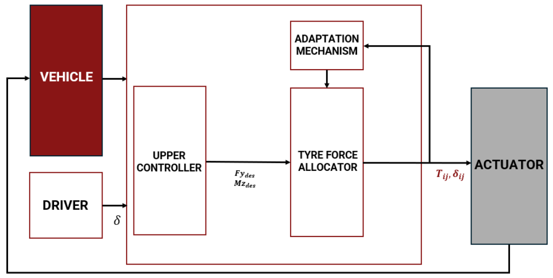


FIGURE 16. Two layer control structure of SBW+4WD vehicles, adapted from [117].

It is also worth mentioning the increasing attention towards path tracking task for vehicles with 4WD/4WS, which is hardly dependent on the benefits derived from improved reachable lateral dynamics behaviour. Moreover, as previously stated, the controller's design phase should also consider sensors and actuators' malfunctions; therefore, fault identification and fault tolerant control approaches have been regarded as a promising research direction [109].

Finally, towards future mobility, a great remark derives from considering energy consumption within IVDC design. The authors of [180] defined a control problem which not only takes into account T_{ij}, δ_{ij} and the camber angle variation of each wheel to optimize manoeuvrability, but also energy consumption has been added. Based on that, a hierarchical three-step control scheme can be introduced [37], [116]. Yaw rate and sideslip angles are firstly decoupled and then a coordinated control is proposed to obtain the comprehensive optimization of vehicle dynamics and it allows the independent development of the single subsystems.

2) STABILITY CONTROLLERS

a: DYC

The choice of EVs represents both an opportunity and a challenge when designing safety-related control logics. Typical applications include the introduction of direct yaw moment control DYC to enhance handling behaviour of the vehicle. It is intuitive how seamless the integration with in-wheel motors can be because of the possibility of obtaining DYC control by applying individual braking/driving torque to each wheel. Yue and Fan [139] proposed a hierarchical solution which consists of a main-loop controller and a servo-loop controller. The former uses a fractional order PID controller to generate the desired external yaw moment and the latter optimally distributes its value to the wheel torque via SQP method. Another example is provided by [140], where the coordination strategy employs a high-level motion controller and a low-level allocation controller (Fig. 17).

Although lane keeping assistance (LKA), lane departure warning (LDW) and lane change assist systems (LCA) have been widely employed, for higher automation vehicles, the

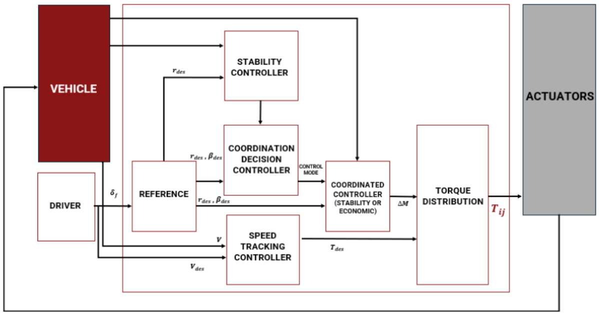


FIGURE 17. **Hierarchical control structure, adapted from [140].**

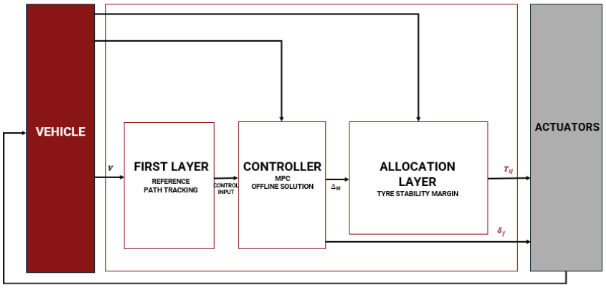


FIGURE 18. **Hierarchical control structure of 4WD+DYC, adapted from [208].**

path tracking task still remains one key enabling feature. An example of application to 4WD vehicles with DYC actuator is proposed by Peng et al. [208] (Fig. 18).

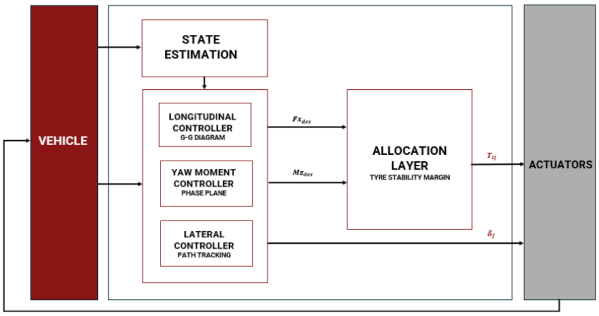


FIGURE 19. **Hierarchical control structure of DYC+AFS, adapted from [166].**

b: DYC+AFS

In the context of tracking a desired path while driving at the handling limits, a study conducted in [166] on Autonomous Grounded Vehicles (AGV) highlighted the possibility of using a multi-level structure for the design of the integrated controller. Three subsystems, namely the longitudinal, lateral and yaw systems, are firstly described. The longitudinal controller evaluates the total traction or braking force, the lateral controller minimizes the error between actual and desired path and determines the desired steer angle and a yaw moment controller ensures handling stability through the sliding mode technique. The lower layer is a common force distribution layer, implemented to evaluate the torque of each independent motor (Fig. 19). On the same topic of AGVs, a similar structure is employed in [169], where the main innovations are presented in the upper layer with the adoption of a super-twisting SMC and an MPC, which are designed to deal with uncertainties of tyres, vehicle parameters and road conditions (Fig. 20).

Another example of a two-level structure is suggested by [167]. The choice between AFS/DYC is mainly based on operation region division, which is directly part of the upper layer (which also evaluates the corrective yaw moment). The execution-lower layer finally generates the corrective steer angle and driving/braking torques. Similarly, in [172], the upper layer AFS+DYC is designed to track the ideal state values and eliminate errors while generating the yaw moment. Accordingly to the typical hierarchical structure, the lower layer is devoted to distribute the yaw moment to the four wheels using optimal control method (Fig. 20).

Moreover, three-level structures are investigated. A multi-objective coordination of a distributed-drive EV with AFS and DYC is proposed in [209]. This work employs the neuro-adaptive predictive control (NAPC) for multi-objective control function including longitudinal dynamics, lateral dynamics and desired levels of motor torque and brake performance (Fig. 21). Based on the same structure, the authors of [171] employed an MPC controller to determine the steering angles of the front wheels according to the driving state for path following and then a coordinated controller to evaluate the yaw moment for the final torque distribution controller (Fig. 22).

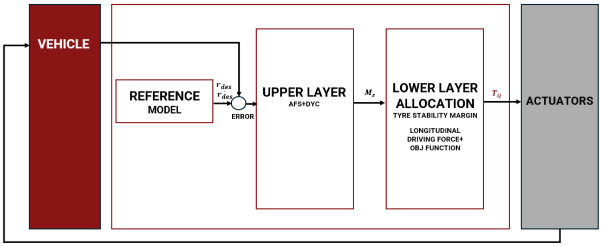


FIGURE 20. **Two layer structure, adapted from [169], [172].**

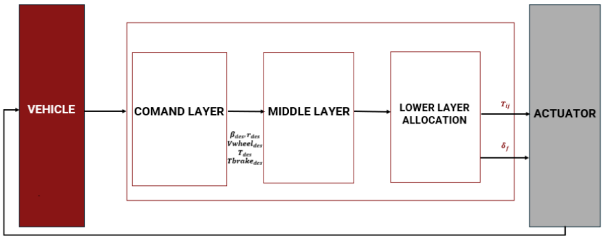


FIGURE 21. **Hierarchical three levels control structure, adapted from [209].**

Improvements to these structures can also be found in [168], where the scheme provides an additional layer based on phase plane stability analysis, which, ultimately, determines the correlation function between AFS and DYC (Fig. 24).

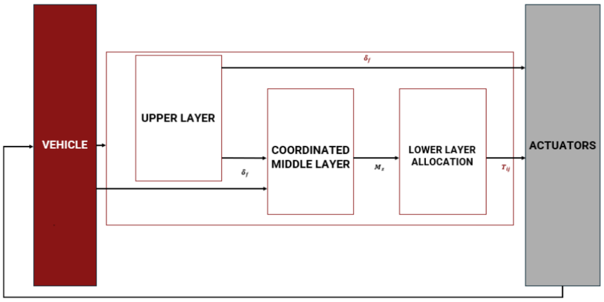


FIGURE 22. Hierarchical three levels control structure, adapted from [171].

Lastly, the rising attention towards energy efficiency for distributed drive EV is underlined in [170], where a two-level scheme is proposed: the first one combines AFS and DYC and then a multi-objective driving/braking torque allocation algorithm is applied. There is an addition of a module dedicated to total energy consumption evaluation through a two-dimensional lookup table (as a function of driving/braking speed and motor rotation speed) (Fig. 23).

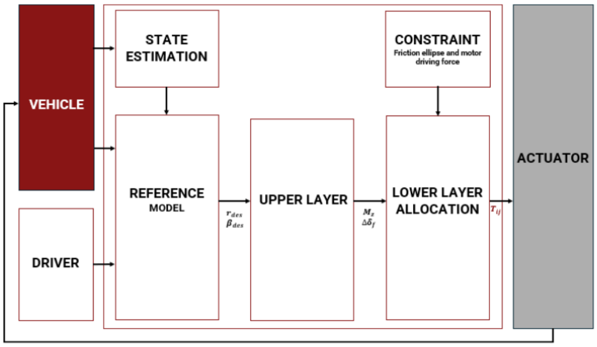


FIGURE 23. Two layer structure with energy consumption module, adapted from [170].

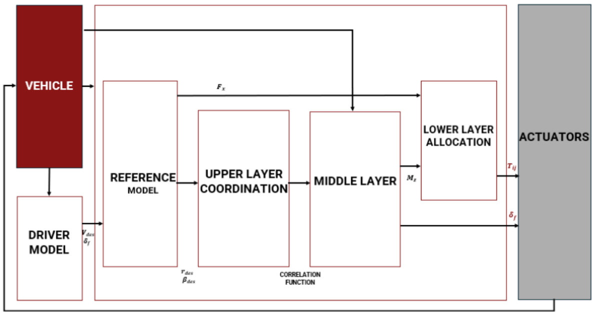


FIGURE 24. Control structure of 4WD+AFS+DYC, adapted from [168].

For the sake of completeness, the application of a yaw moment can also be realized through applying DB torques. The authors of [187] proposed a coordinated chassis control based on three levels: the supervisory layer that acts as a monitor and evaluates the desired yaw rate (based on the steering angle, the vehicle speed and the vehicle dynamics limitation); the upper-level layer computes the desired longitudinal forces and the target yaw moment and then a tyre force control allocation layer is employed to distribute the tyre forces and the steering angle to the specific actuators (Fig. 25). The integration will be based on an optimized control allocation method, namely Fixed-Point (FP). The advantage can be found in balancing the saturation effect of each tyre simultaneously by combining AFS system, DB and 4WD.

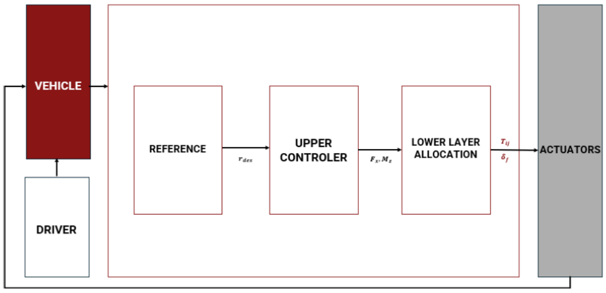


FIGURE 25. Control structure of 4WD+AFS+DB, adapted from [187].

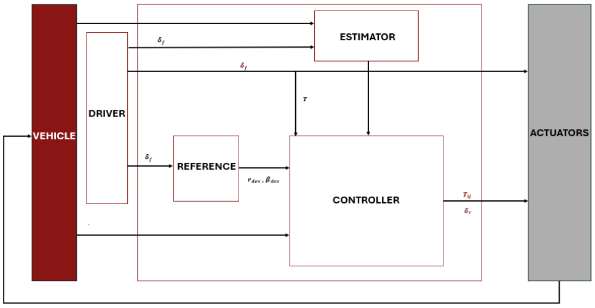


FIGURE 26. Control structure of 4WD+4WS+ARS+DYC, adapted from [191].

c: DYC+ARS

In [191], a three-level vehicle control is proposed, which includes an ideal motion generator, an online tyre model estimator and a stability controller. This solution is suitable for 4WD and ARS equipped vehicles, while the front steering angles are applied by the driver. The ideal motion generator is self-explanatory as it provides desired values of sideslip angle and yaw rate (from a 2-DOF vehicle model) for trajectory tracking control; the coordination strategy is based on Lyapunov theory, starting from the definition of tracking errors. Lastly, a tyre estimator is required by the control allocation algorithm as it needs the knowledge of tyre longitudinal and lateral forces to evaluate the corresponding torques at each wheel (Fig. 26).

Similar work is proposed in [112], where a three-layer structure is defined: first, the perception and judgment layer determines the reference values of yaw rate and sideslip angle; then, a coordinated controller is composed of ARS and DYC, and lastly, the torque and steering angle distribution is done through phase plane stability calculation.

d: ESP+AFS

The work of Yim et al. [179] proposed an interesting set of actuators applied to a hybrid front ICE and independent motor-driven rear wheels. They adopted a two-level structure, where the first generates the control yaw moment needed to stabilize the vehicle using SMC theory and then the lower layer distributes it into the tyre forces. The distribution level is thought to be adaptive depending on the set of actuators employed with a weighted pseudo-inverse based control allocation scheme (WPCA). A set of weights is designed based on the specific combination of actuators, including ESP only, ESP+AFS and ESP+4WD+AFS.

3) VERTICAL CONTROLLERS

a: ASS+4WS

A more general approach involves dealing with a complete integrated control structure: the vertical dynamics of the vehicle are added to the conventional longitudinal and lateral investigation in [210]. The architecture has a hierarchical organization: a driver control layer which represents the reference integrated vehicle model, a body motion control layer that calculates the forces and torques, a tyre force distribution layer that takes into account various constraints and, finally, an actuator control layer allows the achievement of the desired level of tyre forces. Alternatively, older research works [189] include centralized dynamic control based on a hierarchical structure where two levels are introduced. It is also referred to as "distributed" because the global control is distributed from the upper to the lower layers. The first layer evaluates the error between the actual and the target states (position and orientation vector of vehicle body) q and $q_p = [x_p y_p z_p \theta_p \phi_p \psi_p]$ to determine the control forces and torque, which are then applied in the executive lower layer (Fig. 27).

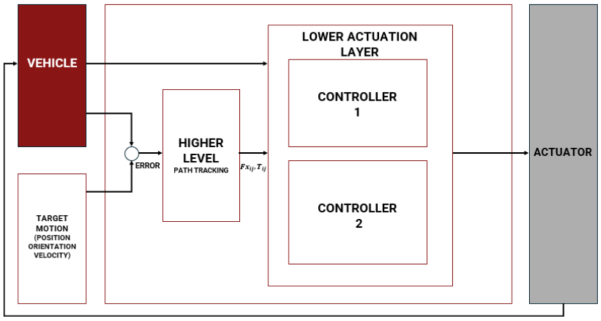
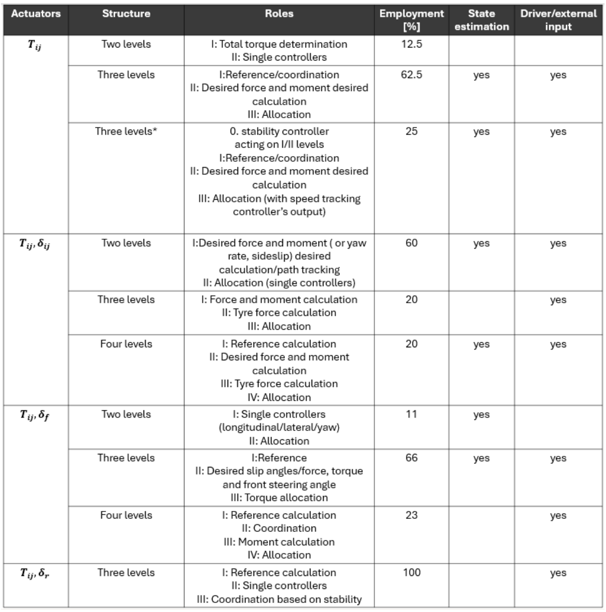


FIGURE 27. **Control structure of 4WD+4ws+ASS, adapted from [189].**



Actuators	Structure	Roles	Employment [%]	State estimation	Driver/external input
T_{ij}	Two levels	I: Total torque determination II: Single controllers	12.5		
	Three levels	I:Reference/coordination II: Desired force and moment desired calculation III: Allocation	62.5	yes	yes
	Three levels*	0. stability controller acting on I/II levels I:Reference/coordination II: Desired force and moment desired calculation III: Allocation (with speed tracking controller's output)	25	yes	yes
T_{ij}, δ_{ij}	Two levels	I:Desired force and moment (or yaw rate, sideslip) desired calculation/path tracking II: Allocation (single controllers)	60	yes	yes
	Three levels	I: Force and moment calculation II: Tyre force calculation III: Allocation	20		yes
	Four levels	I: Reference calculation II: Desired force and moment calculation III: Tyre force calculation IV: Allocation	20	yes	yes
T_{ij}, δ_f	Two levels	I: Single controllers (longitudinal/lateral/yaw) II: Allocation	11	yes	
	Three levels	I:Reference II: Desired slip angles/force, torque and front steering angle III: Torque allocation	66	yes	yes
	Four levels	I: Reference calculation II: Coordination III: Moment calculation IV: Allocation	23		yes
T_{ij}, δ_r	Three levels	I: Reference calculation II: Single controllers III: Coordination based on stability	100		yes

FIGURE 28. **Summary of integrated control structures for various actuators, their employment rate in recent literature works and the roles that each level exerts.**

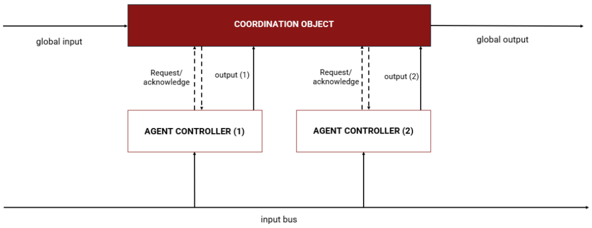


FIGURE 29. **Multi-agent control structure, adapted from [199].**

So far, the integration strategies involved the adoption of centralized hierarchical or multi-level solutions (Fig.28); however, those methods are not designed to be easily reconfigured or extended to include additional control objectives. Traditionally, multi-layered architectures are distributed control structures and, in this regard, agent-based modelling has received intensive attention. This is mainly due to the concept of a network of problem solvers (agents) which work together to solve problems; the agents are autonomous and can be heterogeneous in nature. An example of application of the multi-agent based method to vehicle chassis control (integration of 4WD+AFS+ARS+DB+ABS+ASR) can be found in [199] and it will be better analysed in Section V. The technique is based on coordination rules obtained after analysing the characteristics of the vehicle-handling dynamics and their coupling. Each subsystem is modelled independently from the other; however, the domain of operation is divided into a set of regions and in each region the control priority is given to a particular actuator or controller. After the individual design of each subsystem, its structure should be standardized with the form of the agent. The coordination type of mechanism is employed to organize the local controller agents with a coordination object (Fig. 29). From a vehicle dynamics point of view, the integrated control task is based on preserving lateral stability while maintaining the driver's desired yaw rate and desired longitudinal dynamics. Because for each demand (lateral, longitudinal), the feasible domain can be divided into regions where each controller can be more effective, a fuzzy control is employed in the coordination object to implement the coordination rules.

From the current analysis, it can be stated that, although the type of actuators and number of actuators directly influence the choice of specific coordination strategies or control algorithms, from a design point of view, the multi-level structure can be equally employed. In this context, there is a clear tendency to employ two or three-level structures (Fig. 28) with frequent adoption of state estimation techniques and external inputs from the driver. It should be noted that the structure classification given by the authors does not consider as ''levels'', additional controllers (stability ones, for example) that will be investigated in Section VI. Furthermore, as the study explored more recent control-related applications, there is a non-negligible tendency to explore alternative approaches given the need for flexibility and the absence of general standards of interoperability in designing control structures.

V. ALTERNATIVE CONTROL METHODS

As previously depicted, in the context of integrated control of EV, alternatives to multi-level strategies have been proposed and are gaining rising attention.

The concept of Decoupling controller applied to vehicle dynamics systems was originally introduced with the works of Ackermann [211], [212], where a robust compensator/actuator design for all cars and operating conditions was developed to decouple two modes of the vehicle (front axle lateral acceleration and steering angle/yaw rate). This approach makes the steering angle and yaw rate unobservable from the lateral acceleration with mild dependence on the different operating conditions. Furthermore, this can also be applied for vehicles with additional rear wheel steering because the second input can be used for pole placement without any influence (decoupling property) on the other vehicle's mode.

Subsequently, the adoption of 4WS vehicles induced further research [213] for robust decoupling of lateral and yaw motion, leveraging yaw-rate feedback and accelerometer/velocity measurements. Similar work is presented in [214] to independently control the steering and the sideslip angle of the vehicle by means of a diagonal decoupled closed loop system. The vehicle model is based on lateral and roll dynamics with constant speed. As already depicted, the decoupling between lateral and yaw motion can be achieved by feeding back available measurements of vehicle state, including lateral speed, therefore forcing to estimate or measure it; instead, in [35] only yaw rate, lateral acceleration and longitudinal speed are used. Similarly, in [215], a proportional-integral active front steering control and a PI active rear steering control from the yaw rate error with an additive feed-forward reference signal for the vehicle sideslip angle were shown to be able to asymptotically decouple lateral velocity and yaw rate dynamics.

These methods, however, did not take into account the longitudinal dynamics of the vehicle, assuming constant velocity, acceleration or braking. Lateral models can be coupled with existing longitudinal formulations through the introduction of varying vehicle velocity [216]. Stotsky et al. used the longitudinal velocity applied to vehicle platooning control.

In general, it can be said that there are two types of robust control: triangular and diagonal. Using wheel steering angles as inputs, the dynamics are robust triangular decoupling with disturbance rejection performance. Using only the front wheel steering angle and, by feedback, the yaw error through an integrator, robust triangular decoupling is achieved [217]. On the other hand, the technique of quasi linearization is first proposed based on feedback of longitudinal and lateral velocity, yaw rate and their derivatives in [218]. However, this method simplifies the vehicle model at a non-zero equilibrium, leading to a limited control law. The linear-parameter varying (LPV) method is proposed in [217] for a nonlinear model of velocity-varying 4ws. In [219], the control scheme executes an Input-Output diagonal decoupling based on two varying parameter controllers for both longitudinal and lateral vehicle dynamics.

All the above works define the decoupling strategy by means of converting a coupled system into a number of independent single-input single-output systems; however, they cannot be directly associated to feasible solutions of vehicle integrated control.

Leith et al. paved a first step towards integrated controller development in [220], where the steering controller is based on a simplified vehicle model for the lateral dynamics of 4WS cars with the purpose of decoupling sideslip and yaw rate response. Moreover, through the work of Chen et al [14], the decoupling method is classified as a centralized control architecture to combine ASS and VSC subsystems. The author contributed to define a common procedure for inverse system method consisting of:

- Understand the relative degree of coupling
- Insure that the inverse model exists (through means of algorithms such as the popular Interactor [221])
- Construct the inverse model through Neural Networks or inverse mathematical formulations
- Design a closed-loop controller with a disturbance rejection feature

The integration of AFS, DYC and ASS is also explored through the adoption of a neural network inverse method in [222], while the standalone systems of AFS and ASS represent the subject of [223]. Along with these works, the author of [36] leveraged the inverse system to design a sliding mode controller able to decouple EPS, ASS and ESC into three independent linear integral systems while eliminating the interferences. Steering and suspension subsystems represent, indeed, an interesting subject and the description of the vehicle model coupling requires additional effort to be inverted, thus leading to more complex data-driven solutions as depicted in [224]. It is also necessary to mention alternative methods, such as the differential geometry through feedback linearization, employed in [225] for articulated heavy vehicles to decouple longitudinal and lateral motion.

Newer approaches include decoupling methods as strategies that can synergically interact with already employed frameworks, which include:

- Decoupled vehicle model design: It is well known that if the purpose is to accurately control and track vehicle states, the controller model has to portray nonlinear dynamical behaviour of the system while remaining lightweight from the computational point of view. When dealing with vehicle systems, NMPC strategies are often employed [226], [227]. In this regard, the authors of [113] proved that their utilization can be improved through the adoption of a decoupled predictive model.

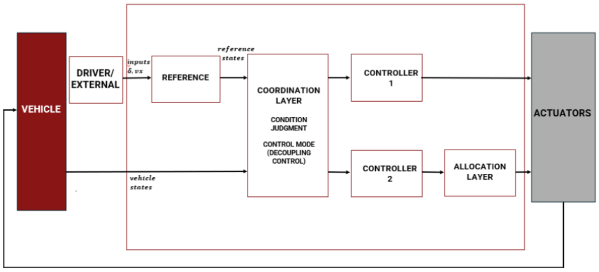


FIGURE 30. Decoupling control method in hierarchical framework, adapted from [228].

- Hierarchical decoupling: Multi-level solutions have been widely adopted and some works present the possibility of leveraging the advantages introduced by decoupling control. The strategy can be adopted on a single subsystem (related to a specific layer) [37] or for specific working conditions as depicted in [228] for slight or moderate steering (decouple AS and DYC, Fig. 30). Lastly, decoupling strategies can be employed in the lower layer to optimally distribute control signals to the actuators [229].
- Motion tracking: It plays an important role in driving safety and comfort in autonomous vehicles. Some researchers directly faced the longitudinal, lateral and yaw coupling problem through the adoption of decoupling methods, able to fully exploit the potential of 4WD vehicle tracking [230]. On the same topic, combining the advantages from decoupled predictive models in [231], a path following scheme was proposed.

A detailed overview of all the cited literature works is presented in Table 6, highlighting various vehicle models (and the relative state vector DOFs), the presence of feedback signals and the measurements needed.

Decoupling control methods are indeed highly dependent on the availability of an accurate vehicle model and the possibility of inverting its dynamics; however, in certain scenarios, the model can be simplified [230] without sacrificing the accuracy. When compared to coupled vehicle control structures, the control problem becomes simplified and the applicability to 4WS/4WD vehicles and AD motion tracking problems has already been investigated. However, some key aspects need to be considered: the necessity of an inverted model can increase the computational burden, the controller does not easily handle constraints and can lead to failures being a centralized framework (Fig. 31,32).

Furthermore, it should be noted that only a few examples of decoupling control in decentralized structures exist, as depicted by [41], [219], and [237] (Fig. 33), this being probably due to control inaccuracies caused by the choice of the structure itself.

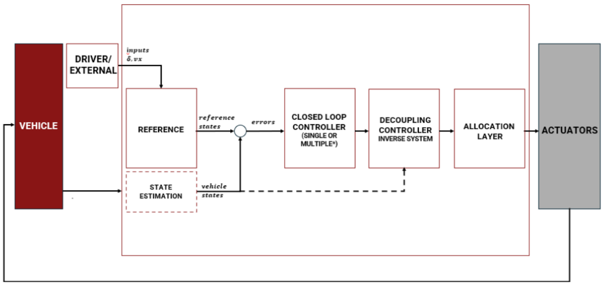


FIGURE 31. Decoupling control method centralized structure (multiple controllers* are presented in [232]), adapted from [14], [173], [224], [225], [230], [233], [234], [235].

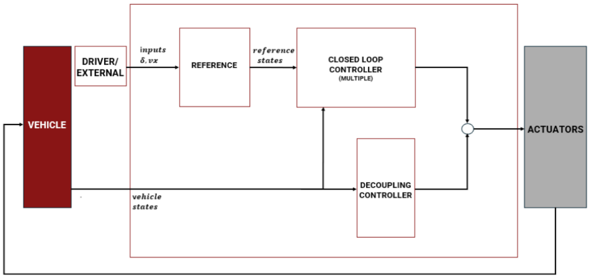


FIGURE 32. Decoupling control method centralized structure, adapted from [236].

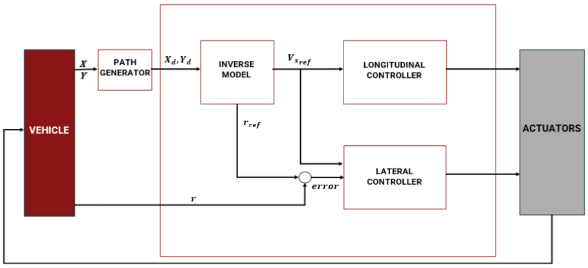


FIGURE 33. Decoupling control method decentralized structure, adapted from [237].

An interesting perspective is the adoption of motion decoupling analysis in conjunction with a hierarchical integrated framework or controllers, thus partially answering what was stated in the motivation. Although the data-driven approach is often not preferred in the vehicle control field, this can be applied to obtain inverse systems able to portray vehicle dynamics at non-coordination levels.

Furthermore, it is mandatory to introduce how the evaluation phase has been conducted; this shows whether decoupling techniques can have a real-world feasibility property. Most of the solutions have been tested through simulation with some exceptions for HIL platform [14], [225], [238] and vehicle testing [220], [223], [224], whereas the performance has been proved through comparison with controllers without decoupling [36], integrated solutions [224], [230], coupled systems [239] and decentralized structures [14].

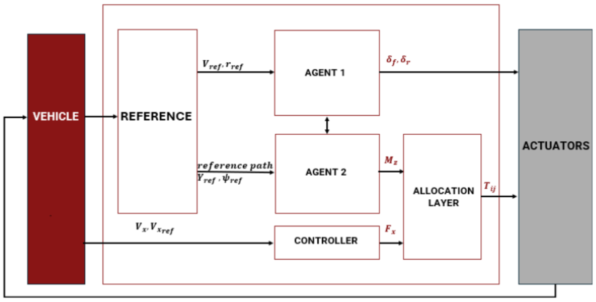


FIGURE 34. **Multi-agent MPC structure, adapted from [41].**

From a control point of view, as introduced in the previous section, the Multi-Agent Strategy (MAS) has been generally applied to multi-vehicle context, including: vehicle communication, engine control, traffic management, lane changing and platooning. Defined as a distributed control strategy in which every agent pursues its own interest and can interact with each other towards a global objective, the strategy finds great suitability with distributed drive EVs while needing lower computational resources, complexity and better handling properties in handling constraints when compared to decoupling methods. This adds to the previous benefit of flexibility, scalability and fault tolerance, providing an interesting approach towards solving the integrated control problem. However, only a few examples refer to single vehicle application; their examination will now be performed. Initially MAS strategy was applied to distributed MPC [41] (Fig. 34) to coordinate steering system and stability controller (DYC). The vehicle model has been firstly rewritten with state and input coupling, then the system has been divided into the subsets (known as agents). This phase is based on identifying control inputs and tracked states and their relative state-space equations. Finally, the controller can be designed and the two agents will use an iterative update algorithm while solving their local optimization problems.

A similar yet simplified approach is used in [42], where the coordination of ABS and AFS has been examined through five agents (four wheels and the centroid). In this work, the vehicle mathematical model is obtained through graph theory [240] and the prediction model for the MPC is based on MAS. While the actuator's inputs remain the same (T_{ij}, δ_f), the structure does not have an allocation layer. Thus, it is only based on the MAS layer with errors as inputs. The steering and stability systems have also been investigated and the cooperative control can be achieved through Pareto-optimality theory to ensure optimal control performance of AFS and DYC [43]. The two agents' control intentions have been, firstly, formulated as objective functions, and then the optimal solution, which minimizes the convex function, is obtained through a Pareto-optimality strategy. Compared to the previous DMPC algorithm, the structure is based on two layers, where the first one is devoted to the cooperation task, and the agents of the real subsystems are displayed. Then, the real systems (AFS and DYC) controllers are employed in the bottom layer to evaluate the steering and driving/braking actuation inputs. The agent model framework was also employed in [100] for the coordination of EPS and ASS, where the belief-desire-intention BDI strategy has been applied through three agents (one of which accounts for the tyre model). The process includes the design of single agents and the controlling strategy to coordinate them; for this reason, another agent has been modelled and receives the feedback from the lower layer agents while evaluating the target parameters for ASS and EPS. It is often the case that the division into single subsets follows particular decomposition techniques, the most employed is the physical distribution (controllers have been developed by different suppliers), but also operation regime division exists and different sets of working conditions have been associated with specific controllers. In case of controlling multiple subsystems such as AS+ASR+ABS+active driveline, one solution could be to coordinate their action through rules [199], here the single components have been modelled using a sliding mode controller that takes into account disturbance as the result of cross coupling effects on single agent. In general, the presented technique requires the vehicle modelling phase, a single subset "agents" design step and a coordination technique.

Since the aim is to discuss alternative technologies that can be beneficial to real-world applications, the suitability of MAS strategy in specific vehicle morphologies is discussed. Indeed, the authors will refer to Simulation or HIL validation due to limited in-vehicle testing. Regarding EV 4, the work of [241] derives from defining in-wheel-motors EVs as intrinsically multi-agent systems. The authors provide a three design models strategy to map the physical longitudinal motion to the control world. This work, however, only deals with longitudinal and wheel dynamics. Recently, a dual-axle EV 2 vehicle has been considered in [242] where the coordination of longitudinal and vertical dynamics represents the authors' aim. The complex vehicle is decomposed into two agents, each selects its action independently and then a centralized training leverages global information. The same vehicle morphology has also been treated for lateral control in [43].

Based on the above considerations, alternative methods may have strengths and flaws depending on the application; therefore, a comparative analysis, including the most suitable vehicle morphologies for each strategy, is presented in Table 7.

VI. FUTURE RESEARCH DIRECTIONS

A. STABILITY BASED CONTROLLERS

The knowledge of the system's dynamics is often the basis for controller's design, e.g., MPC (Model Predictive Control) [136], [208], [261]. It is common to employ simplified/linearized equations to reproduce the dynamics of a highly nonlinear plant (such as the vehicle). Moreover, the increasing attention towards stability analysis has led to various methodologies in order to deeply understand the system and its limits [262], [263], [264], [265]. In this context, based on the application, the adoption of simplified bicycle 2DoFs or 3DoFs models is widespread due to mathematical/computational issues along with interpretability of the results. In the field of vehicle control, some approaches have been proposed and briefly summarized in Tab. 8. Those approaches can be categorized according to their purpose: the coordination task is indeed relevant in the context of multiple subsystems, the most frequently being AFS+DYC and 4WS+4WD. For stability domain definition, they usually employ Phase Plane methodology based on lateral dynamics bicycle model. The plane is described by either $\beta, \dot{\beta}$ or β, r and the coordination is usually dependent on specific thresholds. However, most of them are highly subjective (or obtained through simulations/experience) and do not adapt to varying working conditions. One example can be the usage of indexes such as: $PPS = |1/A\ \dot{\beta} + B1/A\ \beta|$ [112]; its value will be iteratively compared with a threshold to determine whether the system is in a critical, non-stable or stable region. In general, the index value is then fed into a lower level controller, as an actual weight, to distribute the contribution of different subsystems (this is usually performed by means of logic rules). The stability limits (e.g., their boundaries in the phase plane) can also be represented with the adoption of more complex indexes, such as the stability degree introduced by [250] or IDIS, which represents the integrated deviation of the current state from the ideal stability region [255]. This can be represented including the distance of the current sideslip angle and yaw rate from their boundary values. The exact formulation can be found in [255]. Furthermore, as there is a strong dependence on the value of road friction coefficient, velocity and steering angle, the determination of the boundaries needs to rely on those parameters [147] to accurately represent the vehicle system. Ultimately, researchers underline the benefits of stability-based coordination control: the possibility of reducing the coupling while maximizing the performance by exploiting the advantages of different operating regions. Furthermore, some works refer to stability-based design of controllers as depicted in [31] where the DYC subsystem generates the corrective yaw moment based on the following PD control law: $M_z = K_p\ e_{\beta\ \dot{\beta}} + K_d\ d/dt\ e_{\beta\ \dot{\beta}}$. Independently from its purpose, Phase Plane methodology requires the knowledge of hard-to-measure variables (e.g. sideslip angle and its derivative) resulting in a necessary adoption of sensor-fusion or state estimation techniques. However, in presence of full-state measurement available, stability analysis can be employed to obtain envelopes for the controlled system.

1) ENVELOPE CONTROL

Originally introduced for aircraft applications, the envelope is a set of feasible states in state-space representation of a system. Those states may portray stable, obstacle free trajectories, serving for multiple purposes (their definition will be shortly discussed). Besides their introduction, the aim is to force the system within those envelopes by adopting a protection technique which can imply that the controller will search the solution within the envelope or will be activated whether the system falls out of the stable trajectories. Envelope protection can result in control efficiency [266], driver's intent augmentation [258], [267], obstacle avoidance/lane keeping [268] and increased performances while maintaining the system stable. Regarding the envelope definition, the first type of methodologies starting from 2010 were aiming at stabilizing the vehicle at limits on handling, giving rise to handling envelopes. Those were based on sideslip angle, yaw rate Phase Plane calculation to define the sliding surface [269], [270]. The authors of [271] also proposed alternatives allowing the controller to exploit higher yaw rates in transient manoeuvrers. Augmentation to that concept was introduced in [272] where the yaw acceleration isoclines were proposed along with an inner boundary proportional controller. The idea was to align the direction of the boundary with the open loop dynamics of the system in the phase plane. With respect to driver's intent augmentation, it should be noted that in common control logics, the driver's intent is inferred from a linear model and a limited set of measurements. However, while on the one hand the controller should eliminate infeasibility due to handling limits, on the other hand, the linear model implies only linear solutions, strongly reducing the accessible handling regimes. Therefore, the adoption of handling envelope can enhance the overall performance while exploring stable trajectories. In addition to handling, Environmental envelopes were added by [273] in 2013. Those were describing collision free trajectories constraining the vehicle's future lateral deviation from the nominal path within feasible gaps in form of tubes [273], [274]. However, these envelopes aimed at describing the lateral motion of the vehicle, neglecting the importance of longitudinal dynamics and combined slip interactions. To overcome this issue [166] adopted a G-G diagram representation for the definition of the speed profile for longitudinal controller. Therefore, more recently, the concept of Driving envelope was introduced by [267], [275], and [276] and translated in form of constraints on front and rear slip angles: $\alpha_{f,min} < \alpha_f < \alpha_{f,max}$; $\alpha_{r,min} < \alpha_r < \alpha_{r,max}$. Later in [277], same concept was applied to slip ratios $k_{f,min} < k_f < k_{f,max}$; $k_{r,min} < k_r < k_{r,max}$ and extended to combined slip through ellipsoidal boundaries that restrict the capability to brake/accelerate during cornering manoeuvrers [266], [278]. Obviously, the boundaries can also be translated into steering constraints depending on the architecture of the controller [268], [279]. Furthermore, for specific applications (narrow track vehicles), one may need boundaries on specific DoFs of the vehicle (roll, roll rate) in addition to classical yaw rate, rear tyre slip angle [280]. Another remark is the difference between open-loop envelopes, which are generally conservative (neglecting

TABLE 6. Literature review of decoupling control strategies grouped by actuator system (FWS = Front Wheel Steering, RWS = Rear Wheel Steering, ST = Single Track, DT = Double Track, I/O = Input/Output, MO = Multi Objective, Int = Interactor).

	Date	Application	Objective	Method	Input Vehicle Model	Output Vehicle Model	Feedback	Measurement	Vehicle Model	Uncertainties
FWS/RWS										
[243]	1990	FWS, RWS	r, δ_f not observable from a_y	Triangular + pole placement	$a_y, r, \delta_f, \delta_r, r_{ref}$	$\dot{a_y}, \dot{r}, \dot{\delta_f}, \dot{\delta_r}$	$\dot{\delta_f} = r_{ref} - r$, $r_{ref} = f$(steering)	Gyros for r	Linear ST	m, V
[244]	1993	FWS, RWS	r, δ_f not observable; a_y not from δ_r; yaw damping by δ_r	Triangular + prefilters	$\beta, r, \delta_f, \delta_r$	$\dot{\beta}, \dot{r}$	r to δ_r, δ_f	Gyros	Linear ST	wind, braking under mu-split
[212]	1997	FWS	Decouple lateral and yaw motion	Triangular	β, r, δ_f, M_d	$\dot{\beta}, \dot{r}$	r to δ_f	–	Linear ST	torque/force
4WS										
[211]	1994	4WS	r unobservable from α_f	Triangular	α_f, α_r, r	$\dot{\alpha_f}, \dot{\alpha_r}, \dot{r}$	r, δ_{ref}, a_y to δ_f	Gyros, potentiometers, acc.	Nonlinear ST	F_y, V, m
[213]	1994	4WS	Damped yaw dynamics	Triangular + prefilters	$\alpha_f, \alpha_r, r, a_{y_{ref}}$	$\dot{\beta_f}, \dot{r}, \dot{\delta_f}$	$r, \dot{\delta_f} = wf - r$	Gyros, acc.	Nonlinear ST	m, tyre, sidewind
[218]	2000	4WS	Velocity and yaw control	Quasi-linear I/O + robust	$V_x, V_y, r, \delta_f, \delta_r, F_x$	$\dot{V_x}, \dot{V_y}, \dot{r}$	Yes	Gyros, sensors, observer	Linear ST + long.	V, m, Iz, tyre-road
[220]	2005	4WS (SBW)	Decouple β and r	Diagonal + PI	δ_f, δ_r	β, r	Yes (velocity)	–	Linear ST	Yes: Iz, C_f, C_r, m, tyre
[214]	2006	4WS	Control roll and lateral motion	Diagonal + I/O	δ_f, δ_r	β, ψ	Static feedback	Angular sensors or estimator	DT + roll	disturbance, brake
[35]	2006	4WS	Decouple lat/yaw, reduce lag	Triangular + I/O	δ_f, δ_r	r, V_y	V_x, r, a_y	Accel. + gyro (no Vy)	ST	wind, tyre
[245]	2009	4WS	Path tracking (dual steer)	Diagonal + SMC	$\beta, r, \delta_f, \delta_r$	$\dot{\beta}, \dot{r}$	Yes	Path sensors, r,Vx, observer	Linear ST	C_f, C_r, wind, path radius
[215]	2010	4WS	Lat/yaw + lag reduction	Triangular + PI + FF	$\beta, r, \delta_f, \delta_r$	$\dot{\beta}, \dot{r}$	Yes	No V_y, a_y	Linearized	road, V
[246]	2012	4WS	Decouple long./lateral	Quasi-linear + I/O	$V_x, V_y, r, \delta_f, \delta_r$	$\dot{V_x}, \dot{V_y}, \dot{r}$	Yes	Observers	ST + long.	V, disturbances
[217]	2014	4WS	Lat/yaw control	LPV + triangular	$V_x, V_y, \delta_f, \delta_r, F_x$	$\dot{V_x}, \dot{V_y}, \dot{r}$	Yes	Observer + acc.	ST + long.	C_f, C_r, m, Vy, disturbance
[219]	2014	4WS	Decouple V_x from V_y, r	Diagonal I/O	V_x, V_y, r, δ_f, δ_r, F_x	$\dot{V_x}, \dot{V_y}, \dot{r}$	Yes	–	Linear ST	Yes
2WD/4WD										
[247]	2013	4WD	Control yaw, pitch, roll	Transformations + rules	DOFs + forces	$a_x, \dot{\beta}, \ddot{z}, \dot{r}$	–	–	Multi-DOF	road
[235]	2014	2WD rear	Eliminate β, r coupling	NN + Int + PI	β, r, δ_f, M_z	$\dot{\beta}, \dot{r}$	Yes	Observer	Linear 4 DOF	–
[232]	2018	4WD	3rd-order pseudo-lin	Inverse + Int + PID + μ synth.	$\beta, V_x, r,$, δ_f, M_z, F_x	$\dot{\beta}, \dot{r}, \dot{V_x}$	Yes	–	Nonlin ST + long.	via μ
[234]	2020	4WD	Tracking accuracy	Inverse NN + Int+ controller	X, Y,ψ,Fx, δ_f,Mz	$\dot{X}, Y\dot{d}ot$,r	Yes: reference acc. (long., lat., yaw)	$ax, ay, \dot{r}$, states	3 DOFs	
[231]	2021	4WD	Path following + model for MPC: long. lat. decoupled	Input and state vector+ MPC	Vy, r, δ_f, Mz+path following	$\dot{Vy}, \dot{r}$				Cf, C_r (adaptive law)
[230]	2021	4WD	Decouple long. lat. yaw	Inverse NN+Pseudo-linear+ controller	X, Y, ψ, Fx, δ_f	$\dot{X}, \dot{Y}$,r	Yes: reference on ax, ay	ax, ay, X, Y, $\psi, r, \dot{X}, \dot{Y}$	Linear 3 DOFs ST	
AFS										
[248]	2009	AFS (SBW)	Decouple + yaw damping	Triangular + 2nd-order	β, r, δ_f	$\dot{\beta}, \dot{r}$	Yes	δ_f, r, ay, observer (Vy)	Linear ST	–
Other / Integrated Systems										
[216]	1997	Platooning	Lat/long decoupling	Triangular + VSS	$F_{yf}, F_{yr}, \beta_f, r$	$\dot{\beta_f}, \dot{r}$	r	r, v, a	ST + long.	Yes: drag, engine
[233]	2006	AFS, 4WS, 4WD, ASS	Global inverse control	Inverse + feedback	Opt. inverse sys.	F_{tot}	Yes	Yes	–	disturbance observer
[222]	2014	AFS, DYC, ASS	Reduce coupling	NN + Int + PD	$\beta, r, \theta, \delta_{driver}$, δ_{comp}, M_z	β, r, θ	Yes	β, r, θ	Multi-DOF	via NN
[14]	2016	VSC, ASS	Comfort + handling decoupling	Int + I/O matrix + PID/fuzzy	DOFs	$r, \beta, \ddot{z}_{CG}, \theta$, susp. deflection	Yes	$r, \beta, z\ddot{C}G, \theta$	7 DOFs	Yes
[37]	2016	4WD, 4WS	Energy + decoupling	Hierarchy + triple step controller	$\beta, r, \delta_f, \delta_r$ + F_x, F_y, M_z	$\dot{\beta}, \dot{r}, \dot{V_x}$	Yes	V_x, β, r	ST + Pacejka DT	–
[223]	2018	AFS, ASS	Eliminate influence	Inverse + Int + NN + robust	$\beta, r, \theta, \dot{\theta}, M_x$	r, θ	–	–	3 DOFs	Yes
[228]	2019	4WD, 4WS, AS, DYC	Decouple β from r	FB+ SMC + PP	$\beta, r, \delta_f(AS)$, $\delta_r(AS)$, $Mz(DYC)$	$\dot{\beta}, \dot{r}$	Yes	r, β(observer), Vx	Linear ST	via SMC
[36]	2019	EPS, ASS, ESC	Decouple (three systems)	SMC on inverse sys.+ Int	β, r,$\theta, \dot{\theta}$, δ_f, Mz, Mx	β, r, θ	Yes: reference β, r and θ	β, r, θ	DT with roll	pre compensation on SMC
[236]	2019	DD EV	Decouple long. lat.	Robust radial basis NN + FB	β, δ_f, r, Vx, Mz, Fx	$\dot{\beta}, \dot{r}, \dot{Vx}$	Yes: MPC and reference	β, r, Vx	8 DOFs: lat. and long. of the wheel	compensation (uncertainties)
[224]	2021	AFS, susp.	Decouple into SISO	Int+ NN (inverse)+ PID	β, r,$\theta, \dot{\theta}, \delta_f, Mx$	$\dot{\beta}, \dot{r}$,$\dot{\theta}, \ddot{\theta}, r, \theta$	Yes: r_{ref},θ_{ref}	β, roll angle,r	3 DOFs: lat., yaw and roll	
[238]	2022	SAS	Decouple	Decouple model (eis)+ FB H_∞	z_i, θ_i, $\dot{z_j}$, Fz, Mx	$\ddot{z_j}, \ddot{\theta_j}$	Yes		Half car	uneven road by H_∞
[237]	2022	Self driving Tractor	Decouple Long. from r	Inverse kinematics model+controller +PID + Pure pursuit +AS	Vx, Vy	$\dot{X}, \dot{Y}$	Yes:r_{ref}, x_{ref}, y_{ref}	IMU (X, Y, r)	2 DOFs kinematic	
[113]	2024	4WD/4WS	decoupled nonlinear prediction model	Computational decoupling +lower decoupling control	$Vx, Vy, \dot{\theta}$, $, r$, X, Y, ψ, θ, δ(wheel deflection), ax	$\dot{X}$,$\dot{Y}$,$\dot{\theta}$, r, X, Y,θ, ψ	Yes	X, Y, θ, ψ, deriv.	Multi DOFs modified MF	
[225]	2024	AHV, FWS, DD EV	Decouple long. lat.	Differential geometry LB lineariz. + Robust	Trailer/Tractor DOFs	Yes: reference on Vx , r and hinge angle	β, Fz_i, r, Vx trac/trail, δ_f	Nonlinear (LUT) 3DOFs with long.	robust side winds and slope	
[229]	2024	DD EV	Decouple, optimal distribution of drive torque	Hierachical: yaw,roll, pitch +decoupled MO	$\beta, r, \delta_f, \delta Mz$	$\dot{\beta}, \dot{r}$	Yes		ST	robust MPC for uncertainty and multiple I/O const.
[249]	2024	4WD/4WS	Decouple, mitigate rollover	Hierarchical: decoupling MIMO + trigger+ allocation	Vx, Vy, r, θ, δ, Mz	$\dot{Vx}, \dot{Vy}, \dot{r}, \dot{\theta}$	Yes on roll (FB lineariz.) SISO	Vx, Vy, r,roll angle	Nonlinear 4 DOFs with long., lat. yaw and roll	

Centralized	problem • Predictability • Precision • Global optimization • Integrability with model-based controllers • Handle disturbances/uncertainties • Integrability with ML techniques	• Non fault tolerant • Scalability	• Combining steering, stability and vertical actuators, especially for 4WD • Platooning control	*4WD, 4WS, AFS, EPS, DYC, VSC, ESP, ASS, SAS*		🟥
MAS Distributed	• Flexibility • Scalability • Reliability • Fault tolerance • Handling constraint • Complex systems	• Communication/coordination • Standards • Limited integrated solutions	• Coordinate steering and stability • Coordinate Steering and braking	EV2, EV3, EV4, ICE FWD, ICE RWD, ICE 4WD *ABS, AFS, DYC, EPS, ASS, ASR*	S, H	🟨

Purpose	**Actuators**	**Method**	**Effects**	**Index**	**Validation**	**Reference**	**Date**
Coordination	4WS+4WD	PP 2DOF (lat.)	V, μ	PPS	H	[112]	2022
			V, μ, δ_f	stability degree + constraint on r	S	[250]	2024
			$\delta_f, \delta_r, \mu, V$	β	S	[251]	2024
					S	[252]	2024
	DYC	PP 2DOF (lat.)	μ, fuzzy logic	$y_1\,\dot{\beta} + y_2\,\beta$	S	[32]	2015
	4WD	PP 2DOF (lat.)	μ	β and r (threshold on experience)	S, H	[140]	2019
	AFS+DYC	PP 2DOF (lat.)		$1/16\,\dot{\beta} + 1/8\,\beta$	S	[253]	2017
					S	[254]	2022
	DDAS+VSC/4WD	PP 2DOF (lat.)		$b1\,\dot{\beta} + \beta$	S	[197]	2018
	AFS+ASS	PP 2DOF (lat.)		$1/6\,\dot{\beta} + 7/12\,\beta$	S	[132]	2015
						[33]	2016
	ESP+TV	PP 2DOF (lat.)	μ, δ	$\dot{\beta} + 4\,\beta < 30\,\mu$	S	[147]	2017
	ESP+ARS	PP 2DOF (lat.)	vehicle para, V, μ	β	S	[164]	2018
	4WD,AFS+DYC	PP 2DOF (lat.)	V, μ, δ_f	β and r IDIS	S	[255]	2024
			V, μ			[256]	2018
Stable trajectory for PT	4WD+AFS	PP 3DOF (v_y, ω_y, r)	V, μ, δ_f	Stability boundaries	H	[257]	2023
Envelope	AFS+DYC	G-G diagram	μ			[266]	2017
		PP 2DOF (lat.); $\beta - r$ + MF	V		E		
	SBW	PP 2DOF (lat.) $\beta - r$				[258]	2019
	AFS+DYC	PP 2DOF (lat.)		$1/24\,\dot{\beta} - 4/24\,\beta$		[31]	2006
C design and coordination						[95]	2016
	AFS/ARS+TV	PP 2DOF (lat.)				[259]	2004
C design, vehicle/C behavior		PP 3DOF (v_y, ω_y, r)	$k\,\mu$			[260]	2018

the transient overshoot) and closed-loop ones which result in less driving-friendly solutions. The latter allows the possibility to explore conditions at handling limits whose achievement can only be experienced by expert drivers [281]. Lastly, Dynamic envelope (DE) was recently introduced for articulated multi-body vehicles as spatial boundary that encompasses the maximum lateral, longitudinal and vertical displacement of the system's structure during its motion [282]. This can be closely related to road geometry, vehicle configuration and steering control strategies: DE : $w + tan(max(\chi))l + y_m$. Where w is the vehicle width and y_m is the lateral margin. Similarly, considering the width and length of the vehicle and the feasible road path, the authors of [283] proposed a dual inner and outer envelope to ensure safety of AVs during path tracking task. The second phase is to design a controller able to keep the system within the previously introduced envelopes. This phase is regarded as envelope protection and its potential has already been fully explored in aircraft with full-time-full-authority control, where the driver can be overridden by the controller's restriction, thus leading to risk minimization. Various authors proposed techniques for envelope protection:

- Sliding Mode Control: it is widely employed for handling uncertainties and in case of envelope control the sliding surface can be defined as a linear combination of the two states (yaw rate and sideslip) [166], [269], [270], [272]. $S = (r - r_{safe}) - q(\beta - \beta_{safe})$. Where β_{safe}, r_{safe} are the closest points on the safe boundary in the Phase Plane and q is the line slope.
- MPC: The majority of literature works tend to adopt the predictive model with envelope limits in the form of linearized constraint [258], [267], [271], [277], [279], [284]. Moreover, due to the necessity to find the optimal solution, the adoption of a slack variable is common to soften the constraints on the defined envelopes [273], [274], [278], [280]. For the sake of completeness, along with constraints, when dealing with multi-objective functions to be minimized, weighting factors can be chosen accordingly. The dynamic requirements can be modified through weighting factors to reflect different conditions in which the priority of one control objective changes among the others [285].
- Others: Similar to coordination stability-based controllers, the envelope can be employed to regulate the control authority through a weighting factor [268]. The factor will then be used by the H_∞ controller in the lower layer of the structure. Furthermore, a cascaded control structure is employed for front and rear slip protection in [276]. For front slip, an inverse kinematics model is employed, while for rear both feedback and feed-forward control are proposed.

Finally, it is necessary to mention that, although the stability analysis has a disruptive potential in vehicle control, envelope definition usually originates from reduced order/simplified vehicle models; the most used being the

TABLE 8. Literature works on stability in the context of integrated vehicle control. (C = Controller; PP = Phase Plane; S = Simulation; E = Experiments,H = Hardware in the Loop; PT = Path Tracking).

Purpose	Actuators	Method	Effects	Index	Validation	Reference	Date
Coordination	4WS+4WD	PP 2DOF (lat.)	V, μ	PPS	H	[112]	2022
			V, μ, δ_f	stability degree + constraint on r	S	[250]	2024
			$\delta_f, \delta_r, \mu, V$	β	S	[251]	2024
					S	[252]	2024
	DYC	PP 2DOF (lat.)	μ, fuzzy logic	$y_1\,\dot\beta + y_2\,\beta$	S	[32]	2015
	4WD	PP 2DOF (lat.)	μ	β and r (threshold on experience)	S, H	[140]	2019
	AFS+DYC	PP 2DOF (lat.)		$1/16\,\dot\beta + 1/8\,\beta$	S	[253]	2017
					S	[254]	2022
	DDAS+VSC/4WD	PP 2DOF (lat.)		$b1\,\dot\beta + \beta$	S	[197]	2018
	AFS+ASS	PP 2DOF (lat.)		$1/6\,\dot\beta + 7/12\,\beta$	S	[132]	2015
						[33]	2016
	ESP+TV	PP 2DOF (lat.)	μ, δ	$\dot\beta + 4\,\beta < 30\,\mu$	S	[147]	2017
	ESP+ARS	PP 2DOF (lat.)	vehicle para, V, μ	β	S	[164]	2018
	4WD,AFS+DYC	PP 2DOF (lat.)	V, μ, δ_f	β and r IDIS	S	[255]	2024
			V, μ	β	S	[256]	2019
Stable trajectory for PT	4WD+AFS	PP 3DOF (vy, vy, r)	V, μ, δ_f	stability boundaries	H	[257]	2025
Envelope	AFS+DYC	G-G diagram	μ		E	[166]	2017
		PP 2DOF (lat.). $\beta - r$ + MF	V, δ				
	SBW	PP 2DOF (lat.). $\beta - r$			E	[258]	2016
C design and coordination	AFS+DYC	PP 2DOF (lat.)		$1/24\,\dot\beta + 4/24\,\beta$	S	[31]	2006
						[95]	2016
	AFS/ARS+TV	PP 2DOF (lat.)		β	S	[259]	2004
C design, vehicle/C behaviour		PP 3DOF (vy, vy, r)	$\delta, k\ \mu$		S	[260]	2018

bicycle model [270] with linear [276]/Fiala [269], [271], [281]/Pacejka [273], [274], [275], [277], [279] tyre model. This strongly affects the accuracy of the analysis in complex unmodelled system scenarios. Regarding the application, most of the works refer to the use of steer-by-wire actuators [258], [269], [270], [271], [282] or autonomous vehicles [274], [279] applications.

Indeed, the most promising feature is the possibility of designing a computationally simple controller [272] that can enhance the robustness of the system while improving the real-time feasibility of complex integrated optimization problems.

B. ADAPTIVENESS

This subsection aims at exploring the concept of adaptiveness, which originates from the need to design a controller able to adapt to dynamic scenarios. As previously introduced, both the external environment and the vehicle, with its nonlinear nature, contribute to the complexity of the problem. Most of the researchers originally investigated the design of controllers in the presence of model uncertainties and varying parameters. It is well known that, when choosing a model-based framework, the knowledge of parameters is essential and often they are set at their nominal values, neglecting their variation. In general, both tyre parameters and road conditions are subject to changes depending on thermal-pressure effects or external environmental conditions. Indeed, tyre cornering stiffness [231], [286], [287] variation has represented one of the most examined parameters along with road friction [111], [287], vehicle mass and inertia [23], [32], [288], longitudinal velocity [197], [288], CoG height [24], road conditions (weather, crosswind) [289] and road profile (slope). Very few works relate to vehicle suspension and vertical parameters [24], [290]. The first approach consisted of linear robust control against known bounded parametric uncertainties; this strategy was applied to vehicle system to trajectory following purposes [291], [292], [293], [294]. However, deterministic robust control (DRC) requires the knowledge of parameters' bounds and results in conservative solutions. To overcome this issue, nonlinear robust control was introduced. Mashadi and Madiji [295] proposed a sliding mode integrated controller to combine AFS and DYC, while Cho [193] explored tyre cornering stiffness as an unknown parameter to design a chassis controller based on a bicycle model. Another example is from He and JI [296], which introduced a nonlinear robust integrated vehicle chassis controller with parameter adaptation law. Alternatively, adaptive control techniques were introduced to provide closed-loop stability and asymptotical trajectory tracking performance being less conservative than DRC. Those include: adaptive pole placement [297], adaptive sliding mode [298], [299], adaptive MPC [287], [289], adaptive fuzzy controllers [300], [301], neural adaptive controllers [302], radial basis neural networks [303] and are based on certainty equivalence principle [304]. Another common feature is the adoption of quadratic Lyapunov function [23], [93], thus resulting in slower tracking error decays and oscillatory behaviour. Therefore, the adoption of non Quadratic Lyapunov functions can be a promising alternative [286]. Moreover, the injection of bounded disturbances can result in boundless control parameters; to this purpose the parameter projection method [305], [306], [307], [308] was employed. Most of the resulting control signals, however, appear as non-smooth, thus generating issues with the actuators [286]. A recent scheme presents the adoption of Immersion and Invariance approach which is an alternative way to design asymptotically stabilizing and adaptive control laws with respect to Lyapunov functions [309], [310], [311], [312], [313]. On the other hand, the controller can be fed with estimated values of uncertain parameters; this approach, although implying the presence of a module dedicated to parameter estimation, defines a modular design and can be easily integrated into pre-developed control structures. Various methodologies can be employed, including machine learning RLS [287], Neural Network [303] or Kalman filtering technique [24]. Most of the literature works underline the adoption of adaptive control schemes within specific integrated architectures: two [111], [286], [288], [303] or three layers [314] hierarchical/coordinated control [315], cascaded MPC [289], outer and inner loop [23] and decoupled controllers [316], [317]. In the two-layer structures, the upper layer is usually devoted to coordination/supervision while the lower acts as a distribution layer, allocating forces/moments generated by the former. Stability [117], [288], [316], path tracking [287], [314] and comfort [290], [318] represent the most discussed objectives with the combination of AFS+DYC [93], [303], AFS+TV [319] and 4WD+4WS [23], [111], [314]. Regarding standalone vehicle controllers, the most employed are MPC [287], sliding mode controllers [117], fuzzy PID [290] and ML-based solutions [209], [320]. Often, they are based on varying control parameters, weights or constraints. The former can be related to vehicle speed changes, as depicted by [287]. They include: prediction horizon, control horizon and sampling time; their choice heavily depends on vehicle velocity. It has been proved that for higher speed, larger prediction horizons and sampling time should be chosen. Therefore, three sets of parameters have been selected and can be fed to the controller depending on the actual velocity. Weight adaptation also represents a great strategy, an example is the adaptive mechanism presented in [317], where the weight on the increment of the control output is changed to reduce violent variations when the lateral error suddenly increases. Furthermore, an interesting approach is combining the advantages of stability analysis/envelope definition and the adaptive feature. In [32] fuzzy logic technique is adopted to expand the stability region for every value of vehicle mass and road friction, starting from four different pre-evaluated conditions. More recently, Hashemi and Khajepour [321] proposed a constraint adaptation law to address safety concerns due to road friction uncertainties. The safe operating envelope is expanded/shrunk according to surface conditions based on vehicle sideslip angle increments with respect to the yaw rate.

The adaptiveness feature is also closely related to mode selection, as the vehicle experiences various conditions, some objectives (handling, comfort, stability) could need more emphasis than others. A sliding mode controller with an adaptation mechanism for mode selection has been presented in [117]. A decoupled control problem within an adaptive MPC architecture addressed varying motion behaviours with adaptive weights for lateral dynamics and scenario adaptive constraints for longitudinal controller [317]. Furthermore, the multi-model theory is also being proposed to handle tyre cornering stiffness variation within the design of a convex polytope [231] and, more recently, adapted to different traffic risk levels with a deep adaptive control (RL-based) [320]. Lastly, some combined solutions need to be mentioned: the adaptiveness with respect to working conditions and tyre road friction/optimal slip ratio estimation was introduced in [188], vehicle mass and road estimation, along with mode selection [32] are considered with weighting integration laws within a two LQR framework. Others refer to the possibility of identifying fault operations and driving conditions [322] or actuator faults along with unmatched disturbance and varying controller parameters [323]. This analysis has shown interesting opportunities to augment integrated control structure with precise knowledge of vehicle parameters; however, based on the authors' current understanding, there is a lack in articles which include different/more active control system's integration. While on the one hand, the estimation approach doesn't require a substantial re-design of the control structure, on the other hand, robust control or adaptation laws would compromise the requirement of universal applicability. Recent developments in data-driven identification and learning-based estimation offer complementary means of covering multiple scenarios given a theoretically wide variety of training data, thereby capturing nonlinear behaviours that are otherwise difficult to model analytically. However, leveraging such data richness in practice requires substantial computational capability: high-frequency sensing streams, large-scale parametrization typically demand hardware-accelerated architectures and tightly optimized real-time pipelines. As a result, the computational load and real-world applicability still remain open-issues, along with the lack of safety standards in adaptive controllers. To this end, the possibility of objectively defining benchmarking criteria could be essential. Other promising research directions include: the adaptation to abrupt changes, which are usually not being considered, although representing a critical point, especially for safety-related controllers with road-friction estimation [324] and the lack of articles dealing with the simultaneous variation of all the parameters [325] in the context of integrated controllers.

C. SMART MOBILITY

The environment in which a new technology is being developed can offer substantial opportunities, the employment of future control logic needs to consider the upcoming smart mobility scenario. In this context, communication technologies that facilitate the exchange of critical information (traffic, road condition, road hazards, upcoming signals and signs) can build a robust framework for sensing the vehicle and coordinate its interaction with other entities. In fact, V2x (Vehicle to Everything) can be regarded as a tool beyond vehicle sensing boundaries, given the possibility to overcome standard sensors' limitations (weather conditions and lowlight [326]), thus providing situational awareness and computational efficiency. To the purpose of integrating

V2x technology within standard vehicle structure, the authors of [326] proposed a modular architecture based on:

- Sensing module: it considers the information gathered by all the physical sensors mounted on the vehicle.
- Perception module: it is used to detect possible road users via camera sensors
- Control module: it generates actuators' commands following a designed control logic.
- V2X module: it is used to process incoming messages and to generate output messages on the vehicle's status.
- Vehicle interface: it receives control commands and publishes data about the vehicle's status.

Vehicle controllers will employ preceding vehicles as moving sensors and infrastructures as bridges in a network of multiple players. Some practical applications of V2x are already being explored by the scientific community, including cruise control [327], collision warning, lane change warning/assistance, motion control/path planning [328], [329], suspension control (already employed in production vehicles as suggested by [330] and [331], vehicle platoon [332] and tyre-road friction estimation. In this case, the communication protocol can be supported by other sensor-based on-board state estimators to enhance its effectiveness. Furthermore, recently, researchers have been exploring the benefits of V2V, V2I technology towards energy management [333] or energy consumption with minimization of vehicle delays in a two-layer vehicle trajectory and fuzzy signal timing control [334].

The knowledge of future road information (e.g., curvature) has been exploited since the 1960s with the introduction of preview control. This concept originates from linear quadratic optimal control, with the possibility of dealing with future nonlinear disturbance (road information).

Preview control methodologies can yield analytical solutions through the incorporation of upcoming road information, thereby reducing reliance on computationally intensive numerical optimization methods like Model Predictive Control (MPC). Typical applications include active suspension control [335], [336], driver model [337], [338], [339] path tracking [340], [341] based on LQ [335], [336], SMC [342] and adaptive control [338]. Despite multiple approaches exist, the most employed is the LQ because of the possibility of fine tuning its performance within the objective function [343]. V2V (Vehicle to Vehicle) communication can be adopted as a less expensive and more accurate way to measure road profile for convoy vehicles [344], [345]. Fewer examples, however, refer to preview control applied to active systems such as ESP or Active Roll Control (ARC), this being mainly due to the impossibility of measuring the steering angle a priori. However, with the advent of more sophisticated V2V techniques, the preceding vehicle state (steering angle) can be transmitted backward for preview control. It is also essential to underline that the disturbance in preview controllers is usually sampled over equally spaced time intervals under the assumption that the vehicle speed is unchanged [343]. This assumption can result fragile with varying vehicle speed or varying inter-vehicle distance, leading to the unfeasibility of applying this type of control. To overcome this issue, a position-based sampling was proposed in [343], where the steering angle of the preceding vehicle is obtained through GPS.

Preview controllers can also be regarded as pre-emptive; depending on the application, they can be categorized as:

- Stability-based: knowledge of the expected curvature of the path ahead is used in an NMPC architecture based on double track. The structure employs a driver layer, an environmental layer and a control layer to coordinate the braking action [346];
- Comfort-oriented: knowledge of the road profile can be employed to reduce longitudinal oscillations. An example is found in [347], where the NMPC strategy is applied to all-wheels EVs with in-wheel motors. Likewise, the design of preview active suspension system with longitudinal dynamics is considered in [348]. The methodology employs an explicit MPC and a velocity planning method based on road height information;
- Energy management-oriented: the upcoming era of electrification is marked by increasingly stringent regulations on emissions and fuel efficiency, necessitating the development of advanced energy management strategies. Han and Ahn [349] proposed a novel framework that integrates a Lagrangian function with an MPC scheme aimed at minimizing the defined objective, also introducing the potential for incorporating external information, accessible through emerging V2X communication technologies, as a key avenue for further enhancement;
- Safety-related: obstacle or emergency collision avoidance has been a crucial subject of research in the last decade. In [350], the authors considered the future road profile known for implementing the pre-emptive braking strategy and comparing pre-emptive braking, 4WS and DYC towards the same objective, ultimately demonstrating the effectiveness of such a strategy. Similarly, based on the knowledge of the curvature profile of the road, an NMPC-based pre-emptive controller with environment detection, virtual driver and a drivability layer was introduced in [351], where the authors aimed at exploring various actuator configurations, partially exploiting the integrated control problem with a pre-emptive TV (for 4WD vehicles) solution with varying longitudinal dynamics.

Moreover, in 2022, the authors of [352] underlined the gap between potential vehicle connectivity in enhancing the performance of active control systems, presenting an NMPC structure for pre-emptive traction and braking control, and leveraging the knowledge of future expected path and tyre-road friction conditions.

To the current date, the authors have identified only a limited number of examples where V2X technology has been applied within the context of integrated vehicle control, likely due to the constraints of current communication systems in delivering reliable, real-time, safety-critical data [353]. Limitations as latency, coverage gaps, and inconsistent reliability, can pose significant challenges for high-frequency tasks; consequently, V2X usage has so far been confined primarily to low-frequency, non-safety-critical functions, such as infotainment or limited information sharing [354]. A preliminary work for vehicle platoon management was presented in 2021 in [355], combining lateral and longitudinal controllers that leveraged position and its derivatives from preceding vehicles. To vehicle-following purpose, a 4WD EV has been used as a benchmark vehicle for an integrated control scheme, based on a longitudinal controller with delay compensator and a lateral MPC subsystem. The reference trajectory was derived through off-board information obtained via V2X: vehicle speed, heading angle and position were derived using V2V, while road slope angle and friction coefficient were obtained via V2I (Vehicle to Infrastructure).

However, most of production vehicles have centralized powertrain structures; therefore, an interesting study was conducted in [356]. The authors proposed an NMPC-based formulation for traction control and anti-jerk, which took advantage of ahead tyre-road friction conditions. For the sake of completeness, a preliminary study (which did not take into account tyre-road friction) was conducted by Batra to the same purpose and leveraging the reference slip ratio at the current time provided by V2X technology [357].

Based on the above analysis, there is a noticeable lack of V2X technology adoption in multi-layer/coordinated integrated control framework. As previously highlighted, the employment of external information can enhance standard sensors' accuracy; their cooperation could undoubtedly provide a more fault-tolerant framework, accounting for more severe driving conditions. On the other hand, while latency and delays still represent a challenging issue, managing multiple data coming from infrastructure and other vehicles will require even more powerful hardware solutions.

VII. CONCLUSION

Despite offering promising opportunities for safer and more connected mobility, the path toward a unified framework for implementation, able to encompass integrated vehicle control architectures from current levels of automation to fully autonomous systems and to embed within a broader smart mobility ecosystem, remains largely uncharted. It results clear that further research and standardization are essential to bridge this gap, potentially reducing development time, effort, and costs for both scientific and industrial stakeholders.

In this work, the authors have illustrated how a deep understanding of complex vehicle mechanisms and their interaction with the surrounding environment can inform a more conscious and effective design of integrated control systems, giving particular attention to industrial application cases, that allowed to highlight the divergence between practical implementations and research-oriented approaches.

To this purpose, the authors have first critically assessed the feasibility of applying integrated control frameworks proposed in the literature to existing vehicle architectures, and then have proposed additional consideration of alternative solutions that could extend beyond conventional coordination-based strategies. Given the overarching objective of identifying emerging trends, the study indeed introduces novel perspectives. The exploration of stability regions has demonstrated to hold for disruptive potential for the development of computationally efficient, system-aware control logic. The need for adaptive control solutions within integrated architectures has also been examined. Furthermore, the ongoing paradigm shift toward smart mobility has been analysed, emphasizing how the increasing availability of data can enhance the reliability and robustness of integrated vehicle control systems, as follows:

- There is no specific structure tailored to a given set of actuators, ultimately highlighting the need for standard guidelines to promote widespread adoption of integrated solutions. Most research proposes coordinated or multi-layer architectures, varying between two to four levels. Research attention should be directed towards complete solutions that encompass multiple actuators, thereby bridging the gap with real-world vehicle configurations;
- Alternative approaches offer great potential towards simplifying the control problem, global optimization and handling of disturbances (decoupling control) or providing fault-tolerant, flexible design (MAS) when compared to standard coordination solutions. However, their adoption requires further research contributions and the possibility of being integrated into a hierarchical structure can become a huge research trend;
- The definition and examination of vehicle's envelope can increase the robustness of the control framework while reducing computational issues in real-time optimization processes. Stability regions can also reduce the coupling effect and act as supervisors to regulate the control authority of different subsystems (single controllers). Great emphasis should be directed towards other methods to estimate the boundaries and incorporate them into control logic loops;
- The adoption of model-based/data-driven approach to sense vehicle parameters will be beneficial to guarantee a more dynamic response of standard controllers. However, further studies should focus on quantitatively assessing the achieved benefits from the introduction of such estimation approaches, especially in the context of safety-related scenarios;
- Pre-emptive or preview controllers can provide substantial benefits, overcoming the limitation of standard sensors and increasing the accuracy in complex environments. This approach, however, is still not sufficiently mature and the adoption of V2X technology in integrated control framework, along with the management of an increased flow of data (delays/latency), will represent a future research trend.

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