ESC on In-Wheel Motors Driven Electric Vehicle: Handling and Stability Performances Assessment

Margerita Montani
Department of Industrial Engineering
University of Florence
Florence, Italy
margherita.montani@unifi.it

Tommaso Favilli
Department of Industrial Engineering
University of Florence
Florence, Italy
tommaso.favilli@unifi.it

Lorenzo Berzi
Department of Industrial Engineering
University of Florence
Florence, Italy
lorenzo.berzi@unifi.it

Renzo Capitani
Department of Industrial Engineering
University of Florence
Florence, Italy
renzo.capitani@unifi.it

Marco Pierini
Department of Industrial Engineering
University of Florence
Florence, Italy
marco.pierini@unifi.it

Luca Pugi
Department of Industrial Engineering
University of Florence
Florence, Italy
luca.pugi@unifi.it

Claudio Annicchiarico
Meccanica42
Sesto Fiorentino (FI), Italy
claudio.annicchiarico@meccanica42.com

***Abstract*—Improved lateral stability performances of modern Electric Vehicles equipped with In-Wheel Motors could be achieved by a proper design of the adopted control strategy. The possibility to independently regulates braking and traction efforts delivered at each wheel can lead to increased handling properties during cornering manoeuvres, especially if performed in degraded adherence operative conditions. In this activity, authors propose a newly ESC lateral stability algorithm, integrated with longitudinal stability controller (EBD and ABS) and implemented on a benchmark vehicle use case model. The assessment of the performances is done through co-simulation activities, imposing to the vehicle specified reference trajectories according to related standards, in order to evaluate the achieved stability improvements.**

***Index Terms*—electric vehicle, in-wheel motor, lateral stability**

I. Introduction

The availability of more and more sophisticated mechatronics and by-wire systems [1] in modern road vehicles offers to designers a wide range of innovative opportunities to improve stability performances [2], [3]. Also, vehicle electrification is a fast-growing technology [5] which could lead to dynamical behaviour enhancement due to their promising characteristics [6]. However, the availability of a Regenerative Braking System (RBS) makes appear the Electric Vehicle (EV) an over-actuated system [7] which require a synergetic integration between available braking actuators and stability controllers [8]. In fact, coordinate RBS and disc brake effort applications, so called *Brake Blending*, is fundamental to ensure minimum required braking performances in every operative condition [9], [10].

Challenging well-known and widely diffused control algorithms is intent of the paper, aiming at the development of effective longitudinal and lateral control strategies which can fully exploit the electric powertrain features and, also, to investigate unconventional driveline architectures that can lead to more performances improvements.

Since the electric powertrain is object of reliability constrains, its integration with different control structures need to consider its operational limits. Thus, the consequent increased complexity in the system architectures and the recent growing interest for In-Wheel Motor (IWM) driven vehicle, requires the development of control strategies which combines the contribution of all the involved stability controllers: Electronic Stability Control (ESC), Electronic Braking Distribution (EBD) and Anti-lock Braking System (ABS) [11]–[13].

Objectives of the work is to correctly integrate proposed longitudinal and lateral stability controllers, in order to validate the results on a benchmark vehicle through simulation activities. In particular, the results are evaluated supposing an alternative drive-line architecture respect to the conventional layout of the vehicle Use Case (UC), establishing corresponding improvement through the execution of several reference manoeuvres, according to related standards.

Respect to previously proposed work in literature, in this paper authors develop a newly ESC strategy using an Unscented Kalman Filter (UKF) vehicle state estimator [2] and More-Penrose pseudoinverse based torque vectoring technique [3], [4], which aim at minimizing the difference between the driving performances requested by the driver and the controllers, ensuring enhanced stable behaviour by fully exploiting IWM traction and braking characteristic.

All the models are developed in co-simulation environments that accurately reproduce the boundary conditions in which the vehicle can operate during real driving scenario.

II. Aim Of The Paper

As already pointed out, intent of these activities is to assess the possible improvement arising by an optimized

978-1-7281-7455-6/20/$31.00 ©2020 IEEE

coordination between proposed stability controllers (ESC, EBD and ABS), in terms of vehicle's dynamical behaviour.

To fulfill these tasks, we decide to build a vehicle model following a co-simulation approach between widely diffused simulation environments: *MATLAB Simulink* and *VI grade Simulator*. In particular, the models developed in the different solutions are coupled using one platform as master and the other one as slave. In order to ensure no losses in the data exchange process during Real-Time (RT) simulation tests, proper sample rates and solvers are imposed.

III. Electric Vehicle Model

The vehicle model, inspired by a real existing car, is a Rear Wheel Drive (RWD) vehicle configuration. However, we suppose a different powertrain layout, in order to investigate the performance improvements allowed by the proposed stability controllers: a Four Wheel Drive (4WD) architectures with IWMs, which independently actuate the EV wheels. Vehicle model consist of several sub-systems belonging to quite different physical domains (e.g. mechanical, electrical, electronic, controlling, and more). The main sub-models adopted for this work are:

- Driver Model: provide the vehicle command, such as brake and throttle demands (both dimensionless signals variable in the [0-1] range), along with the steer command of the front wheels.
- Stability Controller: as already pointed out, we develop ESC, EBD and ABS models. These are interposed between the driver model and the Motor Control Unit (MCU) or the Brake Control Unit (BCU). Detailed characteristics of each controllers are briefly explained in the dedicated sub-section.
- Electric Motor Model: composed by the MCU and the actuators, which reproduce the behaviour of a multi-quadrant operator IWM. The Electric Motor (EM) is controlled in order to trace the ideal power characteristic [5] and to work on multiple quadrants: the 1° during traction phases and the 4° during braking phases.
- Hydraulic Brake Plant Model: developed by Meccanica42 company, is composed by four electro-hydraulic units interposed between the main pump and the caliper of the brake system. Each unit is made by a controller and an electric motor which command the hydraulic plant in order to deliver the target braking pressure to the wheel's caliper. They can be considered as a Controller Area Network (CAN) controlled device and so, can track a target pressure imposed by higher level control systems, thus simplifying the integration of the whole loop.
- Vehicle Model: implement dynamics and kinematics behaviours of the chassis, considering multiple Degree of Freedom (DOF), i.e. longitudinal, lateral and yaw motion. Also, account the interaction effects between tire and road, modelling the contact according to a Pacejka model [14].

The interfacing between the *Vehicle Model* and the *Stability Controllers* is done according the block diagram scheme of Fig.1.

A. *Electronic Stability Program*

ESC system is adopted to control the lateral behaviour of the vehicle's body during cornering manoeuvres. Using a reference vehicle model, the controller firstly calculate the expected yaw rate and side slip angles, in function of the imposed trajectory. Then, compare these values with the ones that the vehicle is effectively experiencing, typically estimated through Inertial Measurement Unit (IMU) sensors platform and Artificial Neural Network (ANN)-UKF algorithm, as reported in [15]. If there is a not negligible error, evaluated with a proper dead-zone, the ESC apply torque vectoring and steering control techniques to ensure the vehicle follows as close as possible the desired states (yaw rate and side slip angle), delivering an equivalent yaw moment and a corrective steering angle, according to the driver's command.

In conventional automotive solution, e.g. Internal Combustion Engine (ICE) vehicles, lateral stability strategies differentiates braking efforts between rights and lefts wheels, generating a correction yaw moment, in order to handling over-steering or under-steering conditions of the vehicle, typically occurring when turning in degraded adhesion scenario.

However, for the reference UC, lateral stability enhancement could be achieved thanks to IWM specifications. Indeed, each actuator can both accelerate and decelerate, increasing the M_{yaw} that could be applied to the vehicle body. Assuming that we can separately control the torques exerted on every single wheel, is possible to improve ESC performances by allowing the single wheel also to traction, in addition to brake.

The proposed lateral control algorithm, shown in Fig.1, is composed by three sub-systems: the *Reference Dynamic Model*, the *Control Estimation System* and the *Control Command Actuation*.

1) Reference Dynamic Model: according to driver commands (steering wheel angle and pedals displacement) the vehicle body reference system vary with time. However, to underline inner vehicle characteristics (manoeuvrability) and control the under-steering/over-steering behaviour of the chassis, estimating the steady state values of the yaw rate (1) and side slip angle (2) it's essential. These variables are expressed as a function of the *under-steering gradient* K, a

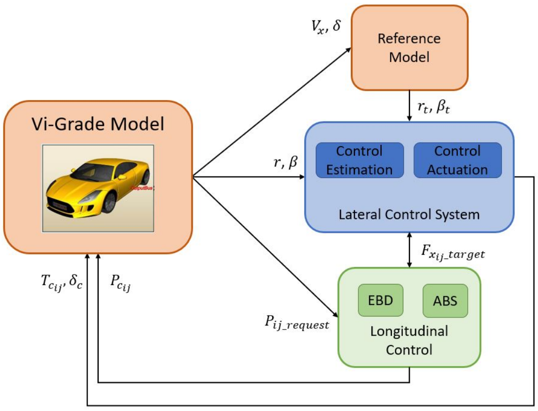

Fig. 1. Lateral Control Strategy Block Diagram

coefficient depending from the vehicle wheelbase $a+b$, mass m and rear tires cornering stiffness C_yr.

$$r_t = \frac{u}{(a+b)+u^2K}\delta \tag{1}$$

$$\beta_t = \frac{b - \frac{mau^2}{(a+b)C_{\text{yf}}}}{(a+b)+u^2K}\delta \tag{2}$$

To ensure a stable behaviour of the vehicle during cornering manoeuvres, the ESC should control the available actuators in order to make the yaw rate r and the side slip angle δ strictly follow their optimal values, established from the *Reference Dynamic Model*. Nevertheless, expressions (1) and (2) doesn't accounts degraded adhesion conditions of the wheels, thus their values must be saturated to an upper threshold, depending on the available friction coefficient in the tire-road contact surface. In doing so, the reference model is implemented to provide the yaw rate and the side-slip angle references, once knowing the steering angle and the longitudinal speed, ensuring that the vehicle remains in grip and handling conditions.

2) Control Estimation System: the implemented ESC strategy is based on a Linear Quadratic Regulator (LQR), an optimal control that is able to find, during driving scenario, the desired yaw torque and steering wheel angle which ensure stable behaviour of the chassis and passengers safety, as well as improved dynamic performances. Conventional LQR estimator works for a single linear dynamic model and are tuned specifically to reset the input variable [16]. The proposed LQR solution, as reported in [2], integrates a gain-scheduling control methodology, able to accurately follows the target value imposed by the *Reference Dynamic Model*, by adaptively tune itself in RT.

The states of the system are the actual yaw rate *r* and side slip angle β, estimated by a single track vehicle model, and yaw rate r_t and nominal side slip angle β_t arises from the reference model by solving (5), where *A* (3) and *B* (4) are the coefficients matrices.

$$A = -\begin{bmatrix} \frac{C_{\text{yf}}+C_{\text{yr}}}{m*vel_x} & \frac{1+C_{\text{yf}}*a-C_{\text{yr}}*b}{m*vel_x^2} & 0 & 0 \\ \frac{C_{\text{yf}}*a-C_{\text{yr}}*b}{J} & \frac{C_{\text{yf}}*a^2+C_{\text{yr}}*b^2}{J*vel_x} & 0 & 0 \\ 0 & 0 & \frac{1}{\tau_\beta} & 0 \\ 0 & 0 & 0 & \frac{1}{\tau_r} \end{bmatrix} \tag{3}$$

$$B = \begin{bmatrix} \frac{C_{\text{yf}}}{m*vel_x} & 0 \\ \frac{C_{\text{yf}}*a}{J} & \frac{1}{J} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

$$\begin{Bmatrix} \dot{r} \\ \dot{\beta} \\ \dot{r}_t \\ \dot{\beta}_t \end{Bmatrix} = A * \begin{Bmatrix} r \\ \beta \\ r_t \\ \beta_t \end{Bmatrix} + B * \begin{Bmatrix} \delta_c \\ M_y \end{Bmatrix} \tag{5}$$

In (5) the dynamic states evolution is expressed by vehicle geometric parameters, i.e., the front and rear wheelbase a and b, the vehicle mass m and yaw moment of inertia J, the front and rear cornering stiffness, C_{yf} and C_{yr} respectively, and the longitudinal vehicle speed, which is scheduled at intervals of 10 m/s.

Defining the output of the controller as the difference between reference and actual states, it's possible to establish the optimal controller gains. This allow to correctly determine the control signals: a steering wheel angle δ_{c}, that has to be added to the driver's steer command, and an equivalent yaw moment M_{yaw}, which is delivered to the vehicle body by the EM and by the hydraulic brake plant (6).

$$\begin{Bmatrix} \delta_c \\ M_{\text{yaw}} \end{Bmatrix} = \begin{bmatrix} K_{\delta r} & K_{\delta\beta} & K_{\delta rt} & K_{\delta\beta t} \\ K_{Mr} & K_{M\beta} & K_{Mrt} & K_{M\beta t} \end{bmatrix} * \begin{Bmatrix} r \\ \beta \\ r_t \\ \beta_t \end{Bmatrix} \tag{6}$$

To be implemented in Real-Time, all the control logic is discretized with a sample time of 0,001 s.

3) Control Command Actuation: the optimal allocation strategy proposed here is based on the Moore-Penrose pseudoinverse [4]. We would like to accomplish two different tasks: (1) ensure a desired stable lateral behaviour of the vehicle and (2) produce a minimum correction moment, which must be also in accordance with the driver intent. The followed approach appear efficient, since minimize the norm 2 of the functional cost (7), which attempt to stabilize the vehicle lateral behaviour, while minimizing the correction efforts.

$$||T_{\text{cmd-k}} - T_{\text{cmd-k}} * ||_2 = (\sum_{k=1}^{n=4} (T_{\text{cmd-k}} - T_{\text{cmd-k}}{}^*)^2)^{1/2} \tag{7}$$

where $k \in \{fl, fr, rl, rr\}$ indicate the wheel (front left, front right, rear left, rear right), y_{k} is the half-track of the corresponding wheel, R_{w} the tire radius, $T_{\text{cmd-k}}$ and $T_{\text{cmd-k}}{}^*$ are the torques requested by the driver and by the ESC controller, respectively.

The reference wheel torques is given by (8).

$$\begin{bmatrix} \frac{-y_{\text{fl}}}{R_{\text{w}}} & \frac{y_{\text{fr}}}{R_{\text{w}}} & \frac{-y_{\text{rl}}}{R_{\text{w}}} & \frac{y_{\text{rr}}}{R_{\text{w}}} \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} T_{\text{cmd-fl}} - T_{\text{cmd-fl}}* \\ T_{\text{cmd-fr}} - T_{\text{cmd-fr}}* \\ T_{\text{cmd-rl}} - T_{\text{cmd-rl}}* \\ T_{\text{cmd-rr}} - T_{\text{cmd-rr}}* \end{bmatrix} = \begin{bmatrix} M_{\text{yaw}} \\ 0 \end{bmatrix} \tag{8}$$

As can be seen, the first row correspond to the task (1), while the second row reflect the task (2). The resolution of (8) occur in four sequential steps. In each *k-th* step the value of $T_{\text{cmd-k}}{}^*$ is checked respect to its upper and lower constrain limits. If it exceeds them, is subsequently saturated at this value. At the *(k+1)-th* steps (8) is recalculated, excluding from the system the row related to the *k-th* torque reference, assumed equal to its own limitations.

The algorithm is parameterized respect to the wheels torque constrains, in order to ensure maximum flexibility and portability of the code respect to different vehicle architectures. This ensure that the requested torques are in accordance with the actuators limitations, allowing, in addition, the implementability of advanced torque vectoring techniques. Is the case of the benchmark vehicle investigated in this paper, in which positive and negative efforts could be delivered independently on each wheel, even of the same axis.

B. Electronic Braking Distribution

The EBD is a control unit widely adopted in the automotive field, used to privilege braking performances of the vehicle's axes, in function of front/rear longitudinal load transfer. According to [17], the set of optimal points, as the adhesion coefficient in the tire-road interface changes, is a parabola, visible in Fig.2(a). This curve is calculated by solving (9), where F_{ij} is the wheel force, with the subscript $i \in \{x, y, z\}$ for longitudinal, lateral and vertical respectively, while $j \in \{f, r\}$ for front and rear axle, the superscript 0 indicate stationary conditions, μ the friction coefficient, h the vertical distance between vehicle Centre Of Gravity (COG) and the ground, l the longitudinal distance between axles.

$$F_{\text{zf}} = \frac{F_{\text{xf}}}{\mu} = {F_{\text{zf}}}^0 + \frac{h}{l}(F_{\text{xf}} + F_{\text{xr}}) \tag{9}$$

The curve define the load distribution coefficients between the axes which, for the specified friction coefficient, maximize the available deceleration while avoiding wheels sliding. Typically, conventional EBD controller approximate this function with a simple ramp which apply a 50/50 ratio axle braking, leaving to the ABS controller the burden to avoid rear wheels sliding (Fig.2(2)).

Use more conservative strategy could reduce the onset of wheel slippage, but underestimate the available deceleration performances, not allowing to completely exploit the braking actuators and reduce the stopping distance for degraded friction conditions. However, the new architecture of by-wire system used allows to reduce the delay respect to the one in modern EV, thanks to the positioning of the hydraulic component close to the wheel. The use of four independent actuators ensures to obtain the optimal brake distribution and increases system safety with redundancy. In order to compensate the uncertainty of the adhesion coefficient we adopt a parabola which slightly deviate from the ideal curve (Fig.2(3)). In this way the front/rear braking allocation strategy appear more robust respect to error in the friction value estimation.

C. Anti-Lock Braking System

To ensure the stability during braking actuation and improve the handling of vehicle, both in longitudinal and cornering manoeuvres, an ABS is recommended (Fig.1). It is implemented a proportional integral derivative (PID) controller that allows to follow the target longitudinal wheel slip

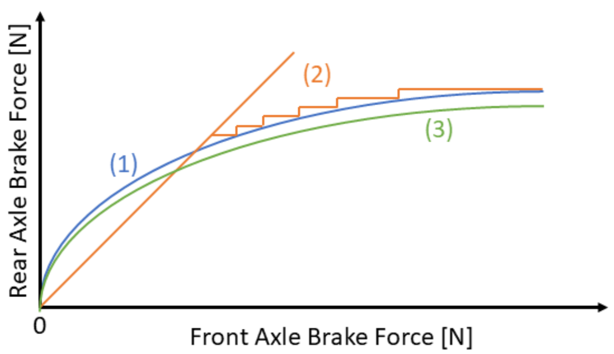

Fig. 2. Front/Rear Axle Braking Force EBD distribution: (1) Ideal; (2) Conventional; (3) Proposed.

[18], given by the ESC and by the driver's request, at each wheel. In this way it is possible to avoid the wheels locking when braking, reducing the corresponding stopping distance and the under/over-steer behavior of vehicle in cornering scenario, ensuring a stable behaviour in accordance to the driver steer input. The target wheel slip is calculated from the desired longitudinal force, arising from the EBD in case of brake pedal actuation, or from the ESC system. Knowing the longitudinal front and rear stiffness of the tires and assuming a linear behaviour of the latter, target longitudinal slip is calculated through (10).

$$\sigma_t = \frac{F_x}{C_x} \tag{10}$$

This value is saturated from zero, so that the control only works when braking, to near 0.05, ensuring that the wheel maintain itself in the linear dynamic range.

Instead the actual value of the longitudinal slip is estimated by (11).

$$\sigma = \frac{V_x - \omega * R_w}{V_x} \tag{11}$$

The PID output is the single pressure which, if applied on every wheel, reduce the error between target and actual value of the slip.

IV. Simulation Campaign Results

To evaluate the stability performances improvement allowed by the controllers, we make the vehicle perform specific reference manoeuvres. Simulation tests on the proposed EV model, implemented in the co-simulation environment of *MATLAB Simulink* and *VI Grade*, could be grouped in two branch: *Longitudinal Stability tests*, useful for the assessment of EBD and ABS effects on the braking distance; *Lateral Stability tests*, executed to understand the impact of the ESC system on the vehicle lateral behaviour.

A. Longitudinal Stability Test

Consist in the execution of straight-line deceleration for several friction coefficient values. Indeed, for degraded tire-road adhesion conditions, EBD and ABS controller are essential to ensure the minimum braking performances required by the standards [19], reducing the corresponding vehicle braking distance. In specific, current regulations recommend a stopping distance under 40 meters for nominal friction values. Results are showed in Fig.3 and summarized in Table I for the vehicle UC, supposing the availability and unavailability of the ABS controller, to highlight its contribution on the stopping distance reduction, showing also the corresponding improvement in terms of distance percentage.

B. Lateral Stability Test

These simulations campaign are executed in order to asses the effect of the proposed ESC algorithm on lateral stability performances. Two different tests are executed: the *Double Lane Change (DLC)* [20] and the *Sine With Dwell* tests [21].

For the DLC, tests are repeated increasing the reference speed, until the vehicle is able to correctly perform the trajectory, supposing availability and unavailability of the proposed controlling method. The improvement are evaluated observing the maximum speed at which the vehicle executes the imposed steering manoeuvres without leaving the admitted zone and hitting the corners (Fig.4).

The performances evaluation of the ESC during the Sine with Dwell manoeuvre (open-loop test) is done evaluating two key parameters: the side slip angle β and the yaw rate r. This test consist of a maneuver, performed at 80 km/h, in which the steering wheel angle is linearly increased until to a lateral acceleration of 0.3 g is reached. Then, the steer angle must follow a sine function at 0.7 Hz frequency, while the amplitude depend of the value established at the stage before. The test is assumed accomplished if the yaw rate of the vehicle returns to zero in a time less than T_0 (the time required to the steer angle to reach its reference) plus 1.75 s. Fig.5 shows the target and actual values of the yaw rate and the side slip angle. Plots displays both the signals the vehicle is experiencing, supposing availability and unavailability of the controller.

The assumption to alternatively suppose availability and unavailability of the stability controller is done in order to comparatively asses the simulation outputs of the performed tests. In particular, the results of the tests in which the controller systems are disabled are assumed as a reference baseline for the metrical evaluation of the obtained improvements.

TABLE I
STOPPING DISTANCE OF THE LONGITUDINAL STABILITY TESTS FOR DIFFERENT ADHERENCE CONDITIONS

Initial Speed: $V_{x\text{-}i}$=27.78 [m/s]			
Adherence μ [0-1]	***ABS***	***Stopping Dist. [m]***	***Improvement [%]***
1	ON	32.56	18.13%
	OFF	39.77	
0.7	ON	44.14	29.02%
	OFF	62.19	
0.3	ON	62.12	22.17%
	OFF	79.82	

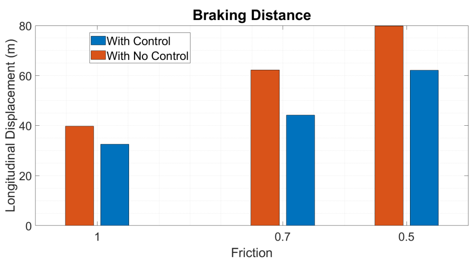

Fig. 3. Vehicle braking distance in longitudinal braking maneuver with a speed of 100 km/h and a friction coefficient of: 1, 0.7 and 0.5, supposing availability and unavailability of the ABS control system.

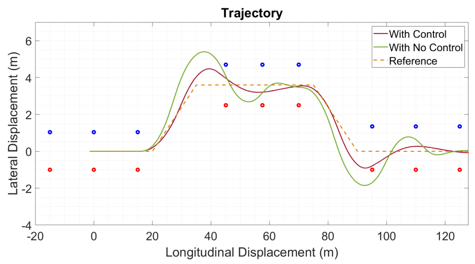

Fig. 4. Vehicle trajectory in a Double Lane Change maneuver, with a longitudinal speed of 50 km/h and a friction of 1, supposing availability and unavailability of the ESC control system.

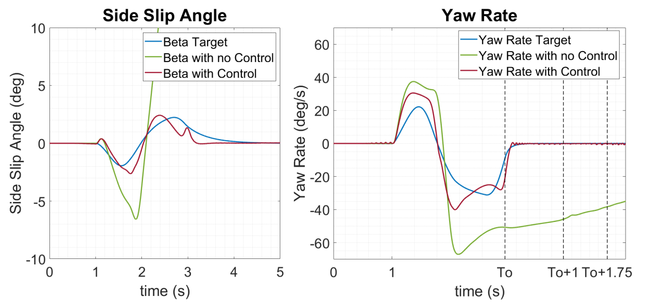

Fig. 5. Target and effective vehicle side slip angle β and yaw rate r during Sine With Dwell maneuver, with a longitudinal speed of 80 km/h and a steering wheel angle of 270 deg, supposing availability and unavailability of the ESC control system.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

Most interesting output of the performed tests campaign concern the dynamical vehicle behaviour improvements allowed by the proposed controllers, both respect to longitudinal and lateral stability.

Assessment of the longitudinal stability enhancement is done in accordance to [19], evaluating the stopping distance of the vehicle, assuming fixed boundary condition. Result of Fig.3 and Table I suggest that the ABS controller is fundamental to ensure a safe behaviour during straight line deceleration. Indeed, for different adherence conditions, the Anti-slip strategy appear effective, since reduce the corresponding longitudinal distance between the starting of the brake manoeuvres and the completely stopping of the vehicle, if compared with the case in which ABS controller is disabled. It's interesting to note also that, for normal adherence conditions, the adopted policy successfully fulfills the limitations imposed by the mandatory standards.

For the lateral stability, we investigate the performance improvements by observing the result of DLC and Sine with D-well tests. Concerning the Double-Lane Change, it can be stated that, looking at the outputs of Fig.4 and Table II, the proposed ESC strategy can ensure a stable lateral behaviour of the vehicle, by increasing the speed at which the reference trajectory could be executed and by reducing the Root Square Mean Error (RSME) respect to the ideal curve of the manoeuvre (centered respect to the admitted zone). Results of the Sine with Dwell tests are visible in Fig.5. The plots clearly show that the ESC controller increase the stability performances, reducing the error between target and real value of β and r during the execution of the imposed manoeuvre.

Summarizing, we can conclude by saying that, in this work, the proposed controller are correctly integrated with each other in order to accomplish enhanced stability behaviours of the IWM driven vehicle, both in longitudinal and lateral directions. Possible future developments concerns the further refining of the vehicle models and sub-models, in order to faithfully replicate real driving scenario conditions, along with a better tuning of the controller parameters, aiming at increasing the stability performances.

TABLE II
MAXIMUM VEHICLE SPEED DURING DOUBLE LANE CHANGE TESTS FOR DIFFERENT ADHERENCE CONDITIONS

Double-Lane Change			
Adherence μ [0-1]	*ESP*	*Max. Speed [km/h]*	*RSME*
1	ON	50	0.52
	OFF	40	0.78
0.7	ON	40	0.40
	OFF	30	0.53
0.3	ON	30	0.11
	OFF	30	0.28

REFERENCES

[1] L. Yu, X. Liu, Z. Xie, and Y. Chen, 'Review of Brake-by-Wire System Used in Modern Passenger Car', in Volume 3: 18th International Conference on Advanced Vehicle Technologies; Charlotte, North Carolina, USA, 2016, p. V003T01A020, doi: 10.1115/DETC2016-59279.

[2] M. Montani, R. Capitani, M. Fainello, and C. Annicchiarico, 'Use of a driving simulator to develop a brake-by-wire system designed for electric vehicles and car stability controls', in 10th International Munich Chassis Symposium 2019, P. E. Pfeffer, Ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2020, pp. 663–684, doi: 10.1007/978-3-658-26435-246.

[3] L. Berzi, T. Favilli, E. Locorotondo, M. Pierini, and L. Pugi, 'Real Time Models of Automotive Mechatronics Systems: Verifications on "Toy Models"', in Advances in Italian Mechanism Science, vol. 68, G. Carbone and A. Gasparetto, Eds. Cham: Springer International Publishing, 2019, pp. 141–148.

[4] J. Jin, 'Modified Pseudoinverse Redistribution Methods for Redundant Controls Allocation', Journal of Guidance, Control, and Dynamics, vol. 28, no. 5, pp. 1076–1079, Sep. 2005, doi: 10.2514/1.14992.

[5] J. de Santiago et al., 'Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review', IEEE Transactions on Vehicular Technology, vol. 61, no. 2, pp. 475–484, Feb. 2012, doi: 10.1109/TVT.2011.2177873.

[6] R. de Castro, M. Tanelli, R. E. Araújo, and S. M. Savaresi, 'Minimum-time manoeuvring in electric vehicles with four wheel-individual-motors', Vehicle System Dynamics, vol. 52, no. 6, pp. 824–846, Jun. 2014, doi: 10.1080/00423114.2014.902973.

[7] C. Feng, N. Ding, Y. He, G. Xu, and F. Gao, 'Control allocation algorithm for over-actuated electric vehicles', J. Cent. South Univ., vol. 21, no. 10, pp. 3705–3712, Oct. 2014, doi: 10.1007/s11771-014-2354-0.

[8] L. Pugi, T. Favilli, L. Berzi, E. Locorotondo, and M. Pierini, 'Brake Blending and Optimal Torque Allocation Strategies for Innovative Electric Powertrains', in Applications in Electronics Pervading Industry, Environment and Society, vol. 573, S. Saponara and A. De Gloria, Eds. Cham: Springer International Publishing, 2019, pp. 477–483.

[9] C. Lv, J. Zhang, Y. Li, and Y. Yuan, 'Regenerative Braking Control Algorithm for an Electrified Vehicle Equipped with a By-Wire Brake System', presented at the SAE 2014 World Congress Exhibition, 2014, pp. 2014-01–1791, doi: 10.4271/2014-01-1791.

[10] L. Berzi et al., 'Brake Blending Strategy on Electric Vehicle Co-simulation Between MATLAB Simulink ® and Simcenter Amesim™', in 2019 IEEE 5th International forum on Research and Technology for Society and Industry (RTSI), Florence, Italy, 2019, pp. 308–313, doi: 10.1109/RTSI.2019.8895548.

[11] K. Sung-Yeon, K. Ji-Weon, L. Sang-Moon, C. Jae-Seung, and K. Hyunsoo, 'A Study on In-wheel Motor Control to Improve Vehicle Stability Using Human-in-the-Loop Simulation', Journal of Power Electronics, vol. 13, no. 4, pp. 536–545, Jul. 2013, doi: 10.6113/JPE.2013.13.4.536.

[12] Kanghyun Nam, H. Fujimoto, and Y. Hori, 'Lateral Stability Control of In-Wheel-Motor-Driven Electric Vehicles Based on Sideslip Angle Estimation Using Lateral Tire Force Sensors', IEEE Trans. Veh. Technol., vol. 61, no. 5, pp. 1972–1985, 2012, doi: 10.1109/TVT.2012.2191627.

[13] B. Jin, C. Sun, and X. Zhang, 'Research on Lateral Stability of Four Hubmotor- In-Wheels Drive Electric Vehicle', International Journal on Smart Sensing and Intelligent Systems, vol. 8, no. 3, pp. 1855–1875, 2015, doi: 10.21307/ijssis-2017-833.

[14] H. Pacejka, Tire and Vehicle Dynamics. Elsevier, 2005.

[15] T. Novi, R. Capitani, C. Annicchiarico, 'An integrated ANN-UKF vehicle sideslip angle estimation based on IMU measurements', in Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 233(7), pp. 1864–1878, 2016.

[16] P. Falcone, H. Eric Tseng, F. Borrelli, J. Asgari, D. Hrovat, 'MPC-based yaw and lateral stabilisation via active front steering and braking', in Vehicle System Dynamics 46, pp. 611–628, 2008.

[17] M. Guiggiani, The science of vehicle dynamics: handling, braking, and ride of road and race cars. Dodrecht: Springer, 2014.

[18] E.Mosca, 'Optimal Predictive and Adaptive Control', in Prentice Hall information and system sciences series, Englewood Cliffs, 1995.

[19] International Organization for Standardization, 'ISO 21994:2007-Passenger cars—Stopping distance at straight-line braking with ABS — Open-loop test method'.

[20] International Organization for Standardization, 'ISO3888-1:1999-Passenger Cars-Test Track for a Severe Lane-change Manoeuvre: Part 1: Double Lane-change'.

[21] International Organization for Standardization, 'ISO 19365:2016-Passenger cars — Validation of vehicle dynamic simulation — Sine with dwell stability control testing'.