Brake Blending and Optimal Torque Allocation Strategies for Innovative Electric Powertrains

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Abstract. Development of electric vehicles is not only an opportunity in terms of environmental sustainability but it also offers interesting possibilities in terms of control performances that can be achieved by on board systems devoted to increase vehicle safety and stability by modulating longitudinal efforts applied to tires. It's not only a matter of performances but also of standardization in a single integrated subsystem able to safely control vehicle dynamics of various functions that are currently implemented by different subsystems. This simplification and rationalization of the whole mechatronic system should be of fundamental importance also for the integration of autonomous or assisted driving functionalities making easier and safer system integration.

1 Introduction: Brake Blending for Automotive Applications

Conventional brake plant adopted for railway vehicle are mainly fluid based being hydraulic solutions [1] preferred for small to medium sized vehicles while for heavy trucks are often adopted pneumatic schemes [2] highly resembling the conventional UIC railway brake [3]. With the growing diffusion of electric traction system in the automotive sector is growing the opportunity of exploiting their four quadrant capabilities in order to perform an extensive use of regenerative braking mainly to optimize energy consumptions and consequently the autonomy of the vehicle both for traction [4] or to fed on board subsystems [5]. The amount of recovered energy is related to the characteristics of the typical driving cycle and it can reach values above 20% of the energy spent for traction, especially in urban-suburban context [6]. This is a clear difference respect to the railway application of regenerative braking where this kind of technology has been originally developed mainly to reduce the consumption of brake friction elements (pads and discs) but it should be a not negligible aspect in terms of improvement of the environmental impact [7]. It should be finally noticed that respect to the corresponding railway application brakes play an important role also in controlling the lateral stability of the vehicle as assured indirectly by systems as the ABS [8] or directly such as the ESP[9]. For this kind of applications superior dynamic response of electric motors should be exploited to further improve stability and controllability performances of vehicles especially when wheels are actuated independently making possible the implementation of Torque Vectoring Strategies [10]. Simultaneous management of braking forces produced by different plant and actuations systems is often called brake blending. Since performances of blended braking plants are associated to different reliability and availability levels, blending system have also to assure the requested braking performances compensating limitations arising from current state of motors, drive and storage systems. In addition, the braking command strategy has to be implemented in order to let the user fully exploit regenerative braking potential while maintaining comfort and intuitiveness [11] for the user. In this work authors propose and describe innovative criteria in order to easily integrate optimal allocation and blending policies able to fully exploit in a relatively simple way torque vectoring capabilities of distributed electric traction system.

2 Reference Benchmark Configuration

In this work authors have considered a generic electric vehicle equipped with independent in-wheel motors that should be used to distribute traction among two or four motors wheels according simplified schemes visible in figure 1/a/b/c.

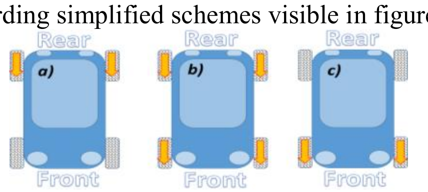

Fig. 1/a/b/c. Inwheel traction motor configurations, two (a,c) or four (b) wheel drive

For the proposed benchmark configuration, authors supposed a nested layout of standards mechatronics systems that have to access to brake actuation reproducing a common scheme which is also adopted by the most widely diffused and simulation software like Siemens Amesim™ [12] as visible in figure 2/a/b: brake demand (figure 2/a) is pre-processed by an EBD system able to optimally distribute braking performances between wheels' respect to an estimated distribution of normal contact forces. Then this brake demand is modified by an ESP system that should be able to activate and modulate brake demand also during the traction phase in order to correct vehicle behavior respect to stability criteria mostly based on a comparison between measured kinematic (yaw speed, lateral acceleration) and an expected one (a tolerated trajectory respect to ideal steering conditions). Finally, generated brake demand is processed by an inner loop corresponding to the ABS system able to modulate brake performances on each wheel in order to optimally exploit available wheel-road adhesion avoiding wheel locking and saturation of the available tangential forces which are potentially dangerous also for lateral stability. Respect to this quite conventional scheme reproduced in figure 2/a, authors considered the following generalized approach in which the plant is generalized respect to a more general and innovative approach which is summarized in figure 2/b: Since electric motors are able to operate in four quadrants the concept of brake demand is generalized in terms of a generic torque, longitudinal traction braking performances which is split among wheels according powertrain configuration and estimated normal contact forces (modified EBD block in figure 2/b). Torque reference on wheels is then modified by the ESP (extended ESP-Torque Vectoring block in figure 2/b) that should modify both traction and braking efforts on wheels according chosen powertrain configuration and different limitations of the involved actuation systems. These reference efforts are processed by a hybrid ABS-ASR subsystem since the sign of processed signals should be both positive or negative being the same system devoted both to control traction and braking maneuvers. Especially in case of braking efforts the system has to manage the application of braking efforts between conventional and electric plant, performing the previously defined blending functionalities. By comparing the two schemes of figure 2/a/b, most noticeable differences among the two plants concern the allocation of longitudinal efforts performed by the extended ESP torque vectoring block and the brake blending one. For this reason, in this short work authors have concentrated their efforts in the description of this two blocks.

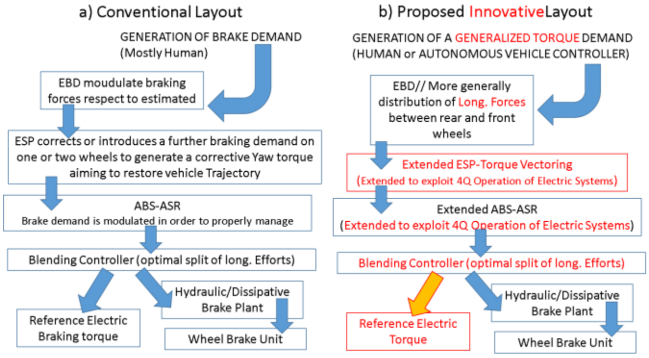

Fig. 2/a/b comparison between conventional a) and innovative b) layouts of the mechatronics on board systems aiming to modulate vehicle braking efforts

2.1 Optimal allocation of efforts for the enhanced ESP system

In order to correct vehicle trajectory, ESP has to allocate a known correction torque M_z which is a function of the error between desired r_{ref} and estimated r_{feed} yaw rotational speed (1)

$$M_z = f\left(r_{ref}, r_{feed}\right) \qquad (1)$$

In order to allocate the torque M_z the effort applied on each wheel should be corrected applying a force T_{Cij} being i and j two indexes describing the position of the wheel (Front, Rear, Left, Right). Applied correction forces has to satisfy at the same time relation (2) and constraints $T_{\min ij}$, $T_{\max ij}$ (3) which depend from availability of both actuation systems (electric motors and mech. brakes).

$$M_z = \frac{1}{2}t\left(T_{fr} - T_{fl} + T_{rr} - T_{rl}\right) = \overbrace{\begin{bmatrix} \frac{1}{2}t & -\frac{1}{2}t & \frac{1}{2}t & -\frac{1}{2}t \end{bmatrix}}^{B(\text{allocation matrix})} \underbrace{\begin{bmatrix} T_{Cfr} \\ T_{Cfl} \\ T_{Crr} \\ T_{Crl} \end{bmatrix}}_{T_C\,(\text{vector of corrections applied by ESP})} \qquad (2)$$

$$T_{\min ij} \le \overbrace{\left(T_{*ij} + T_{Cij}\right)}^{T_{ij}} \le T_{\max ij} \quad (3)$$

In (3) T_{*ij} and T_{ij} represent respectively the reference torque and the corrected one (after the application of T_{Cij}). Since (2) has potentially multiple solutions it should be solved using the Moore-Penrose pseudo-inverse of the torque allocation matrix B as previously experienced by authors in optimal thrust actuation allocation problems for underwater vehicles[13]. Solution obtained with the pseudo-inverse approach is optimal since it minimize the norm of the correction vector T_c : in this way the applied correction is minimal assuring, if possible, the respect of constraints (3). Also a well distributed allocation of efforts between wheels is obtained, this should be very useful especially in degraded adhesion conditions avoiding, as possible. the saturation of available adhesion on wheel-road contact patches. Performed calculation is performed iteratively since at each computational step T_{ij} values that violate constraints (3) are saturated on corresponding limits; then pseudo-inverse calculation is repeated. The use of an iterative procedure it's not a problem since it's possible to demonstrate that even in worst numerical conditions no more than four iterations are necessary while numerical resources needed to calculate the pseudo-inverse matrix of four or less elements is almost negligible.

2.2 Brake Blending Controller

After the efforts T_{ij} have been also processed and further limited by ABS/ASR system respect to available wheel road adhesion the resulting references should be processed by a low-level blending controller which substantially performs operations described in a simplified way by (4):

$$if\left(T_{ij} \le 0\right) \Rightarrow \begin{cases} T_{ij\_ele} = \min\left(T_{ij}, T_{ij\_reg\lim}\right) \\ T_{ij\_brk} = \min\left(T_{ij} - T_{ij\_reg}, 0\right) \end{cases} \text{"braking"} \Bigg| \Rightarrow \; else\; T_{ij\_ele} = \min\left(T_{ij}, T_{ij\_tra\lim}\right) \quad \text{"traction"} \quad (4)$$

According (4) in case of braking efforts blending controller privilege the application of electric efforts (T_{ij_ele}) respect to conventional braking (T_{ij_brk}); in both cases electric efforts are limited respect to constraints ($T_{ij\_tra\lim}$, $T_{ij\_reg\lim}$) that should be easily calculated according powertrain configuration, state and availability of motors, drives and connected energy storage systems.

3 Preliminary Results

Proposed Model was implemented in a preliminary "toy" version using Matlab Simulink 2018a and in particular the new "vehicle dynamics blockset™" which makes available in matlab both advanced vehicle multibody models and relatively detailed models of tyre-road interaction based on widely accepted approach proposed by Pacejka. Potential advantages of the proposed approach should be easily understood looking at some preliminary results visible in figures 3/a/b/c: the behavior of a vehicle with four independent in wheel motors (powertrain layout in figure 1/b), which performs a narrow curve (radius 18m) with degraded adhesion conditions. In this way it can be easily understood the capability of the proposed model of implementing and representing some typical behaviors of ESP and ABS systems.

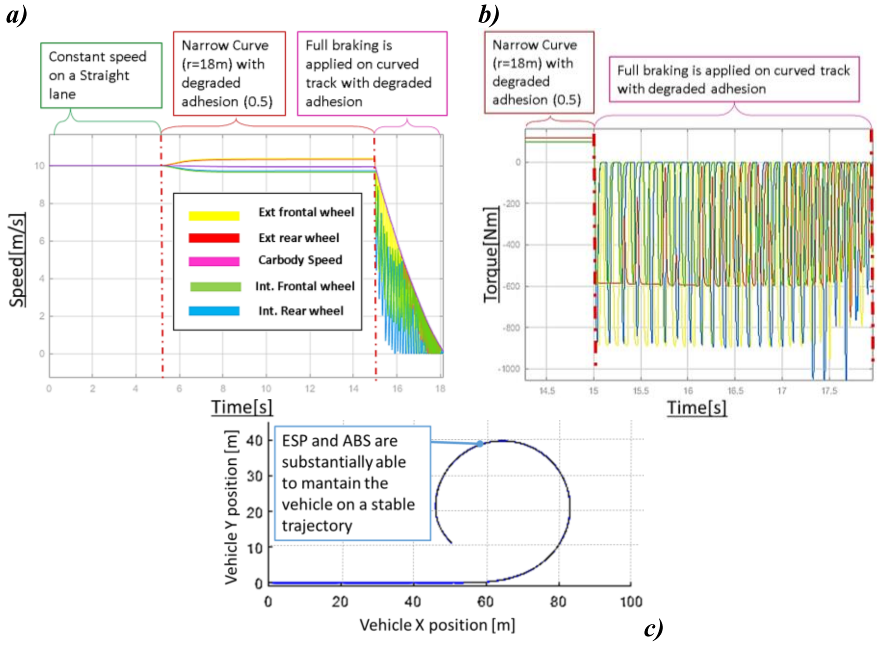

Fig. 3/a/b example of speed a) and torque profiles b) respect to performed trajectory c)

Since the vehicle is equipped with four motors performed maneuvers involve a negligible usage of the conventional brake, with positive consequences both in terms of friction brake and pads (that are not used) and in terms of recovered energy (since all the braking actuation is almost entirely regenerative).

Conclusions and Future Developments

Results of current activities applied to a generic vehicle with distributed traction systems are quite encouraging. As previous step authors are working to a further improvement of the proposed approach hoping to be able to generalize and apply this solution to the largest number of possible “Use Cases” that should be made available by the industrial partners of the OBELICS Project (current results are referred to a preliminary toy model). An extended version of this paper describing in detail both modelling methodologies and obtained results should be the natural prosecution of this preliminary work.

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