

Comparison of Torque Vectoring Control Strategies for a IWM Vehicle

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ABSTRACT

In recent years, concerns for environmental pollution and oil price stimulated the demand for vehicles based on technologies alternative to traditional IC engines. Nowadays several carmakers include hybrid vehicles among their offer and first full electric vehicles appear on the market. Among the different layout of the electric power-train, four in-wheel motors appear to be one of the most attractive. Besides increasing the inner room, this architecture offers the interesting opportunity of easily and efficiently distribute the driving/braking torque on the four wheels. This characteristic can be exploited to generate a yaw moment (torque vectoring) able to increase lateral stability and to improve the handling of a vehicle. The present paper presents and compares two different torque vectoring control strategies for an electric vehicle with four in-wheel motors. Performances of the control strategies are evaluated by means of numerical simulations of open and closed loop maneuvers. Energy demands of the two control strategies are also estimated.

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INTRODUCTION

During last years, interest towards hybrid and electric vehicles has been constantly growing pushed either by environmental concerns and by the continuous rising of oil price. Nowadays, different carmakers include hybrid vehicles among their offer and first full electric vehicles appeared on the market. An interesting vehicle layout allowed in this new generation of passenger cars, is represented by the use of four In-Wheel electric Motors (IWM, [1, 2]). Hybrid or electric vehicles with in-wheel motors offer in fact several advantages: interior spaciousness can be increased thus enlarging design freedom and room for components like batteries. Being the motor directly inside the wheel, no powertrain is required, this leading to the elimination of elements like drive shafts, gearboxes and differential. Drawbacks of IWM are ascribed to the increase of unsprung masses, which is widely accepted to worsen ride comfort and road-holding. Nevertheless recent studies have shown that performance deficit induced by increased unsprung masses could be largely recovered through design changes to suspension compliance bushings, top mounts, passive spring and damper characteristics, etc. [3],[11].

Besides layout advantages, IWM offer also interesting opportunities for the design of active control systems, in particular as far as lateral dynamics control is concerned. The presence of four independent electric motors allows in fact to individually control the driving/braking torque on each wheel; in other words, driving and braking torques can be easily distributed among the four wheels avoiding the complexity and the drawbacks of systems usually equipping today's cars.

Limited slip differentials and semi-active differentials generate the yaw moment by differentiating the driving torque on the wheels; unfortunately in these systems the torque can only be transferred from the fastest wheel to the slowest one. On the other hand, a powertrain equipped with an active differential can overcome this limitation and can control both the amount of torque transfer and its direction [4]; unfortunately, the implementation of such a complicated device is associated with an increase of costs in terms of tuning, space and funding. Brake based systems (e.g. ESP) can instead stabilize the vehicle only with a significant reduction of its speed since the yaw moment is generated by applying differential braking to the four wheels [5, 6, 7]. Other systems like brake torque vectoring (BTV) obtain the desired yaw moment generating traction forces on one side of the vehicle (increasing the engine torque) and developing braking forces on the other side. In this way lateral dynamics of the vehicle can be controlled without reducing vehicle speed. The BTV system described in [8, 9] performs in fact as an active differential, though significant driving and braking torques should be developed and power dissipation in brakes may become a concern.

In principle, torque vectoring is probably the most effective way to generate a yaw moment and, coming back to hybrid and electric vehicles, a layout based on four in-wheel motors seems particularly suitable for this application. Several applications can in fact be found in the literature [1,2,10,11]. The most of proposed control strategies defines torques to be applied by means of IWMs and aimed at improving vehicle handling performance through model-based controllers. This approach requires to estimate the actual motion of the vehicle

and to update reference vehicle model parameters (such as cornering stiffness) whenever working conditions change, e.g. when friction coefficient varies. To address these issues sophisticated state observers must be introduced into the control strategy [6,7,10,12,13].

Aim of the present paper is to further investigate the above mentioned issues in the implementation of a control strategy for torque vectoring of an electric vehicle with four in-wheel motors. Specifically, two control logics are presented and compared. Aim of both the control strategies is to enhance the vehicle yaw-sideslip handling characteristics and particularly its transient response in order to increase safety. The first control logic is based on optimal control theory (LQR) and thus a reference vehicle model (single-track vehicle model) is required to define the control actions. The second control strategy relies instead upon an index (called yaw index in the following), which is directly related to oversteer/understeer behavior of the vehicle. The proposed index is calculated based only on measured quantities, thus number and complexity of estimators/observers needed by the controller are reduced.

A 14 degrees of freedom (dofs) model of a passenger car was used to develop and test the control strategies. The model reproduces the response of the electric motors and of the braking system. A driver model was also included so that close loop maneuvers could be performed. The performances of the two control strategies were eventually compared in a series of handling maneuvers.

THE VEHICLE MODEL

Torque vectoring control has been developed using a 14 dofs model (Figure 1). The dofs of the model are:

- 6 dofs for the rigid chassis (displacements z , y , z and pitch, yaw and roll rotations θ , ψ , ρ , see Figure 1);
- 4 dofs for the vertical displacement of the unsprung masses (z_p , see Figure 1);
- 4 dofs for the wheels' rotation (ω_p , see Figure 1).

The main characteristics of the modeled vehicle (segment D passenger car) are reported in Table 1.

Suspensions' kinematics is introduced by means of look-up tables, while tire-road contact forces are modeled through the MF-Tyre model accounting for combined slip effects.

Table 1. Vehicle characteristics.

Global mass	m	[kg]	1880
Yaw moment of inertia	J_z	[kgm ²]	2873
Wheelbase	p	[m]	2.7
Half-track	c	[m]	0.79

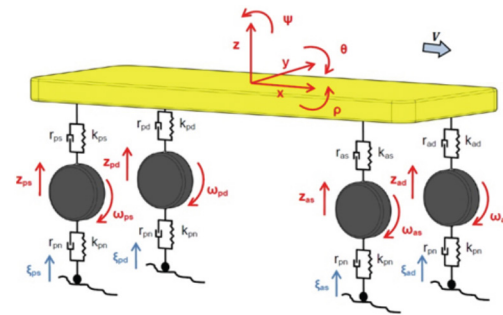


Figure 1. 14dofs vehicle model.

In-wheel motors have been introduced through their characteristic curve torque vs. speed, while their dynamics has been modeled through a first order time lag. This allowed to account for motors bandwidth, nonlinearity and torque saturation at a design stage. In-wheel motors (IWM) data have been gained from [14, 15] and are summarized in Table 2.

Dimensions of IWM are suitable for 18" wheels, which are supported by the considered vehicle.

Table 2. In-wheel motor data.

Peak power @400Vdc	[kW]	81
Continuous output power @400Vdc	[kW]	64
Peak output torque	[Nm]	800
Continuous output torque	[Nm]	500
Nominal input voltage	[Vdc]	200-380
Diameter	[mm]	420
Total motor mass	[kg]	31

Power consumption (P_e) for each motor has been roughly evaluated according to:

$$P_e = T_m \omega_m + k_m T_m^2 \quad (1)$$

where T_m and ω_m are the torque and the angular speed of the motor, while k_m is a constant including power electronics (inverter) and electric motor copper losses [16, 17]. When a driving torque is required losses increase power consumption, while they decrease energy recovery during regenerative braking.

According to [15], the maximum braking torque is limited to 650Nm (equivalent to a vehicle deceleration of about 3m/s²) to avoid an excessive heating of the IWM during regenerative braking. Friction brakes are thus needed to support IWM during braking maneuvers. Friction braking system dynamics has been introduced into the model through a second order dynamics and a time delay constant term.

Steer angle, throttle and braking pedal positions are regarded as imposed inputs characterizing a particular maneuver and they can be either introduced by the user in a pre-processing phase (open loop maneuvers) or computed during the simulation by a driver model (closed loop maneuvers, see next section).

DRIVER MODEL

To allow closed-loop maneuvers, the vehicle model is coupled with a path-follower driver model.

The steer angle allowing to follow a given trajectory is determined based on two error functions (e_1 and e_2 , [18]):

$$\delta = K_1 e_1 + K_2 e_2 \quad (2)$$

where K_1 and K_2 are the driver model gains, while the error functions are defined as:

$$\begin{cases} e_1 = \Delta\psi = \psi_{ref}(s + l_{steer}) - \psi(s) \\ e_2 = d = [P_{refx}(s) - P_{Gx}(s)] \cos(\psi_{ref}(s)) + \dots \\ \quad + [P_{refy}(s) - P_{Gy}(s)] \sin(\psi_{ref}(s)) \end{cases} \quad (3)$$

The error function e_1 represents the difference between the angle of the tangent to the desired path (ψ_{ref}) and the vehicle yaw angle (i.e. it represents the error on the vehicle orientation), while e_2 is the error between the actual position of the center of gravity (cog) of the vehicle (P_{Gx} , P_{Gy}) and its corresponding position along the reference path (P_{refx} , P_{refy} , see Figure 2). It is to point out that, while the error function on the vehicle orientation (e_1) is calculated considering the position the vehicle will have l_{steer} meters in front (preview distance, see Figure 2), the error function on the vehicle (e_2) position considers the actual position of the vehicle. In other words, the driver model looks ahead of l_{steer} meters to anticipate a change in the direction of the path it has to follow, while it keeps the vehicle cog stick to the desired trajectory in the current position. From this point of view, the contribution due to the error function on the vehicle orientation can be seen as a feedforward contribution while the one due to the error function on the vehicle position can be classified as a feedback contribution.

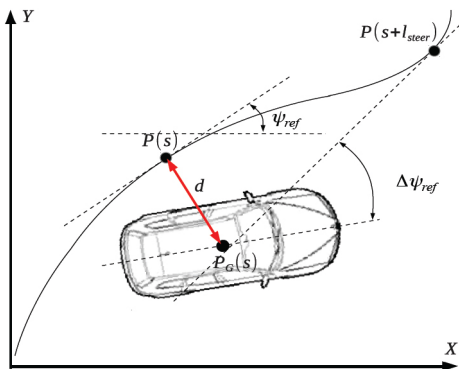


Figure 2. Driver model.

TORQUE VECTORING CONTROL

Two strategies were designed to control the lateral dynamics of the vehicle through independent actuation of the IWM and friction brakes on the four vehicle wheels¹. Both the strategies generate a yaw moment to improve vehicle handling by developing longitudinal forces on the tires; in particular, the two tires of the same axle develop forces with the same magnitude and opposite sign. The yaw moments resulting from control action (thus neglecting braking/traction forces possibly required by the driver) on the front and rear axles ($M_{z,f}$ and $M_{z,r}$) thus are given by (Figure 3):

$$\begin{cases} M_{z,f} = 2F_{x,f}c_f \cos \delta \approx 2F_{x,f}c_f \\ M_{z,r} = 2F_{x,r}c_r \end{cases} \quad (4)$$

In (4), $F_{x,f}$ and $F_{x,r}$ are the longitudinal forces developed on the front and rear right tires respectively, while c_f and c_r represent the corresponding tracks. With respect to systems like ESP, the control logics developed in this work present several advantages:

- the same yaw moment can be generated using only half the longitudinal force required by a system acting only on brakes;
- power consumption is reduced, since the energy required to develop a driving torque on one wheel can in part be recovered during electric regenerative braking of the other wheel of the same axle;
- vehicle speed can be maintained, since driving and braking forces having the same magnitude are applied.

In the following, the two developed control strategies are described. The first proposed control logic is based on a LQR. The second one is instead driven by a yaw-index (YI) accounting for oversteer/understeer tendency of the vehicle.

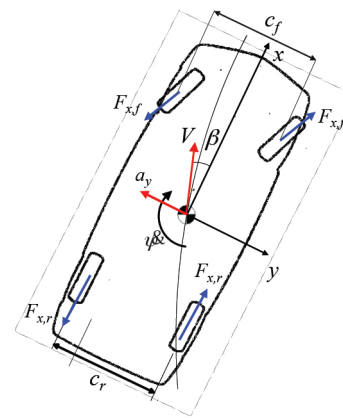


Figure 3. Inner/outer torque distribution and reference system.

1. It is worth noting that the designed control strategies can be applied even to more traditional torque vectoring systems, like active electronic differentials. However in this case, energy regeneration wouldn't be possible.