A state-of-the-art review on torque distribution strategies aimed at enhancing energy efficiency for fully electric vehicles with independently actuated drivetrains

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A STATE-OF-THE-ART REVIEW ON TORQUE DISTRIBUTION STRATEGIES AIMED AT ENHANCING ENERGY EFFICIENCY FOR FULLY ELECTRIC VEHICLES WITH INDEPENDENTLY ACTUATED DRIVETRAINS

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ABSTRACT

Electric vehicles are the future of private passenger transportation. However, there are still several technological barriers that hinder the large scale adoption of electric vehicles. In particular, their limited autonomy motivates studies on methods for improving the energy efficiency of electric vehicles so as to make them more attractive to the market. This paper provides a concise review on the current state-of-the-art of torque distribution strategies aimed at enhancing energy efficiency for fully electric vehicles with independently actuated drivetrains (FEVIADs). Starting from the operating principles, which include the "control allocation" problem, the peculiarities of each proposed solution are illustrated. All the existing techniques are categorized based on a selection of parameters deemed relevant to provide a comprehensive overview and understanding of the topic. Finally, future concerns and research perspectives for FEVIAD are discussed.

Keywords: electric vehicles; torque distribution strategies; energy-efficiency; torque-vectoring; control allocation.

1 INTRODUCTION

During the last few years the interest in electric vehicles (EVs) has developed rapidly due to the decline in fossil resources and to the increasing environmental pollution. EVs are seen as a promising alternative to solve the problem of oil dependence and the global energy crisis [1] [2] [3] [4] [5]. EVs also bring significant benefits with respect to vehicles powered by internal combustion engines. Electric motors respond up to 100 times faster to torque demands, and allow an accurate measurement of motor torque via the motor current [6] [7]. Yet, one of the main obstacles to the success of electric vehicles in the automotive market is their limited autonomy. The current mid-range electric vehicles offer an autonomy around 150-200 km [8], which is significantly lower than that of conventional vehicles powered by an internal combustion engine.

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This issue is being addressed through: i) research on improved battery technologies [9] and on the development of more feasible, light, high energy/power density storage systems (such as supercapacitors [10] [11]); ii) research on optimal torque distribution strategies to improve energy efficiency, thereby increasing EVs cruising range, based on the already available battery/means of electric supply (i.e., without changing battery nor drivetrains, but making the most of the existing layout).

This papers focuses on ii), applied to Fully Electric Vehicles with Independently Actuated Drivetrains (FEVIADs). A FEVIAD (Figure 1) does not have a differential. The wheels are driven either directly, i.e. using in-wheel motors, or using drivetrains consisting of on-board motors and mechanical transmissions [3] [12]. The torque demand of each wheel can be controlled independently. This feature is denoted as torque-vectoring. As a result, the desired behaviour of the vehicle, corresponding to the driver's inputs on the accelerator/brake pedals, can be achieved by an infinite number of torque distributions [12]. Because of this redundancy, an optimal torque distribution can be achieved to maximize energy efficiency. This is known as optimal torque distribution or control allocation (CA) strategy [13].

In the literature there are many studies concerning torque-vectoring on FEVIADs, but not all of them are oriented

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towards the enhancement of vehicle energy efficiency. A FEVIAD can achieve superior vehicle dynamics, handling qualities, safety and drivability through direct yaw moment control [1] [14] [15] [16] [17] [18] [19]. Nonetheless, as discussed in Section 3, direct yaw moment control can be exploited to modify the understeer characteristic of the vehicle purposely targeting energy efficiency.

Additional aspects taken into account by studies on CA strategies include torque fluctuations and switching/clutching operations. It might be required to activate/deactivate one or more drivetrains/motors in some driving conditions (e.g. when the torque demand is beyond the "switching torque" [12], a concept analyzed in Section 3), with effects on driving pleasure [8] [12] [20].

The contribution of this paper is to give a comprehensive overview of the existing torque distribution strategies for FEVIADs, through a careful analysis of the existing literature on this topic.

The remainder of this paper is structured as follows. Sections 2, 3 and 4 analyze all the CA solutions proposed from 2010 to 2019 by various authors. Section 5 proposes a categorization of the existing studies and discusses current issues and possible future developments that should be implemented on FEVIADs. Conclusions are in Section 6.

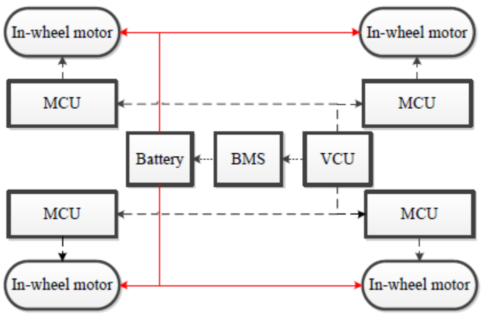

Figure 1. Possible structure of a FEVIAD. VCU: vehicle control unit; MCU: motor control unit; BMS: battery pack and battery management system. Reproduced from [2].

2 EARLY STUDIES: 2010 - 2014

The first formulations of torque allocation strategies aimed at the enhancement of energy-efficiency of FEVIADs were put forward around 2010. A general hierarchical approach for the control of FEVIADs was proposed, and it is being used since. It consists of a high-level supervisory controller that evaluates the desired values of traction/braking force and yaw moment, and a low-level controller that defines the wheel torque demands, i.e. an appropriate CA.

One of the first approaches to CA formulations was from Y. Chen and J. Wang [13]. The adopted strategy was simply based on a predetermined efficiency curve as a function of the torque demand. However the effect of speed was not considered, which is an important limitation. The electric motors were considered as "systems with dual-mode actuators", i.e., able to work both in traction and regeneration. Simulation results proved the proposed technique effective in leading to energy efficiency improvements. According to the paper, which denotes the torque demand as "virtual control", "[...] As the demanded virtual control increases, the algorithm then utilizes both sets of motors […]. The efficiency of the front motor set becomes low with increasing torque […]. This is because that as the required total torque level is high, if only the front set of motors was used, it would work at high-torque-low-efficiency region and thus would consume more power". This is a preliminary definition of the "switching torque" introduced later in this paper and in [12].

Kang et al. [21] described a driving control algorithm using a vehicle model with a front in-line motor and rear in-wheel motors (Figure 2), aimed at improving maneuverability, lateral stability and energy efficiency. The driving controller consists of three parts: i) a supervisory controller regulates the control mode and the desired dynamics which is based on the human driver's inputs, sensor signals, and an admissible control region; ii) an upper-level controller calculates the traction force and yaw moment input; iii) an optimal torque-vectoring algorithm determinates the actuator commands (motors and brakes). Simulation studies showed that the vehicle maneuverability, lateral stability and rollover prevention of vehicle can be significantly improved compared to other driving control algorithms, reducing at the same time the power consumption.

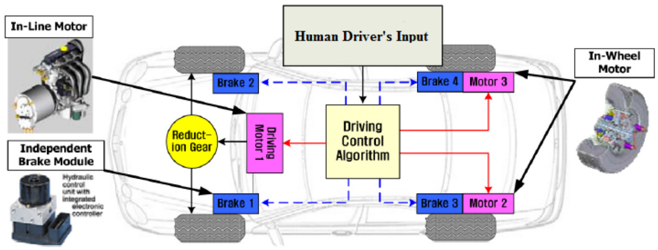

Figure 2. The vehicle body structure proposed by Kang et al. (reproduced from [21]).

One of the most influential authors was certainly A. Pennycott with two important studies [22] [23]. In the first paper [22] a CA strategy was proposed, based on an offline simulation approach. Optimization schemes based on minimizing a direct quadratic cost function of the motor power loss were compared against schemes using look-up tables (based on motor efficiency maps) to determine the motor power loss at different motor speeds and torques. The assumption of a quadratic representation of motor power losses as a function of the torque demand allowed the use of quadratic programming. To examine the influence of different motor characteristics, results for three different types of electric motors were compared, including switched reluctance, permanent magnets, and brushless direct current motors. Comparisons were presented for two maneuvers:

straight-ahead driving and a ramp steer maneuver, both at constant longitudinal acceleration. The results of this study showed that the potential for motor power loss optimization is limited when using a quadratic approximation of the power losses as a function of the torque demand. The paper suggested the need of more complex approximations, and this will be confirmed in further studies [12] [24]. In particular [24] introduced a third order polynomial function to approximate power losses, as discussed later in Section III. Such approximations are generally computationally demanding to solve and may have multiple local minima, which increase the challenge related to their online applicability. This issue was investigated in [23] where the optimal wheel torque distribution was assessed in an offline optimization procedure, and then it was approximated with a simple function for online CA. This was in essence one of the first attempts to implement an online CA method with low computational cost. Simulated straight-ahead driving at a constant speed, ramp maneuver and sequences of step steer maneuvers confirmed that the proposed CA scheme yields savings in the total power utilization compared with a simpler method in which the torques were evenly distributed across the four wheels.

The first considerations on torque fluctuation and clutching operations were made around 2014. De Novellis et al. [20] considered a vehicle model with 2 electric motors (one per axle) connected to the wheels through a gearbox and a TV differential (Figure 3), but above all they were the first to model the losses due to transmission, longitudinal and lateral tire slip. Several objective functions were compared.

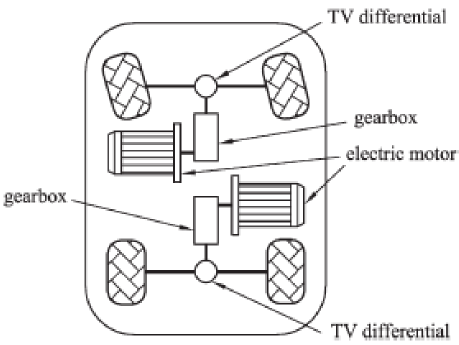

Figure 3. The vehicle model proposed by De Novellis et al. (reproduced from [20]).

Results showed that objective functions based on the minimum tire slip criterion provide better control performance than functions based on motor efficiency. Moreover objective functions based on tire slip distribution allow a smooth variation of the wheel torque values for all achievable lateral accelerations compared to those based on the minimization of motor loss. Using the same vehicle model (2 drivetrains, one per axle) Koehler et al. [8] focused on a method to optimize the number of switching/clutching operations based on the combined efficiency of electric motor, inverter and transmission. The results highlighted a satisfying energy saving especially for low torques, and improved comfort, including some experiments carried out with a Peugeot 3008 Hybrid converted to a FEVIAD.

The first paper to present detailed design, performance, and energy efficiency characterization with experimental results for a FEVIAD was published by R. Wang et al. in 2011 [3]. An experimental characterization of motor torque responses, power consumption and energy efficiency in both driving and regeneration modes was conducted based on the experimental data obtained in chassis dynamometer tests on a prototype FEVIAD developed by Ohio State University with four in-wheel motors (Figure 4). A CA method for improving the vehicle operational energy efficiency was proposed based on the system and component efficiency characteristics, also taking into account the rolling resistance. The results showed the potential for improving the overall energy efficiency by explicitly considering the in-wheel motor efficiency and the operating conditions.

Figure 4. The FEVIAD prototype developed by Ohio State University (reproduced from [3]).

A second prototype vehicle was built in 2013 and the relative experimental results are reported in the study by Gu et al. [4]. They claimed that the required battery capacity is generally proportional to the vehicle size and weight. The experimental FEVIAD was the "Micro-Harry", developed by Tsinghua University and featuring four in-wheel motors (Figure 5). Vehicle tests were carried out to compare the energy efficiency in four-wheel drive mode and in two-wheel drive mode and also to compare the measured and simulated motor efficiency both in traction and (regenerative) braking conditions. Based on the power loss analysis, the conclusion reached was that under all traction or braking conditions the total torque demand should be distributed evenly to all the motors in order to maximize FEVIAD energy efficiency. This conclusion is actually in contrast to those reached later by other authors. This is likely due to: i) the type of motor used, i.e. permanent magnetic synchronous motor (PMSM); ii) the reduced speed at which tests were performed (40 km/h and only in a straight line); iii) the function used to express the total power loss, i.e. still a quadratic function of the torque demand.

Figure 5. The FEVIAD prototype “Micro-Harry” developed by Tsinghua University (reproduced from [4]).

The paper demonstrated that a significant decrease of battery wear and peak values of battery current can be achieved through a HESS, whilst the adoption of the supercapacitor does not improve the overall energy efficiency of the system in nominal thermal conditions, because of the losses in the DC/DC converter. Also, the adoption of an HESS obviously increases space needs and overall weight of the vehicle.

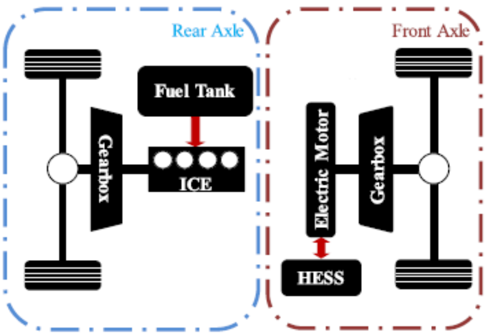

Figure 6. The vehicle model proposed by Santucci et al. (reproduced from [11]).

3 THE YEARS OF MAJOR INNOVATION: 2015-2017

In 2015 the research on FEVIAD energy efficiency experienced a noticeable progress. Pennycott et al. produced a detailed analysis of all the possible sources of power loss during vehicle traction, both for longitudinal and lateral dynamics [25]. The sources of energy loss can be divided into two groups. The first includes loss from the battery, drag resistance, rolling resistance, and transmission. These are not directly influenced by the understeer characteristic or by the control allocation plan. The second group includes dissipation from the motor units and the loss due to longitudinal and lateral tire slip (which depend on the understeer characteristic and on the control allocation plan). The losses from the motor/generator units were determined from motor maps derived from experimental test data. Simulations were performed on a high performance sport utility vehicle with four individually-controlled drivetrains. Three different maneuvers were simulated in this study: straight-ahead driving at different longitudinal acceleration rates, ramp steer at a constant steering rate, and a step steer with a final steering wheel angle of 100°. Different criteria of torque distribution were compared: i) one that used only the front wheels; ii) one that used a front-to-rear uniform distribution; iii) the optimal one, which switches between the other two. The results clearly showed that depending on the driving conditions, the causes of power loss change in a non-negligible way. In particular, in corners with high lateral accelerations, lateral tire slip power losses constitute almost the totality of the loss, which is remarkable. A CA strategy focused solely on motor characteristics may not be the best approach to maximizing energy efficiency. Therefore the results of this study demonstrate the necessity of developing control allocation algorithms aimed at enhancing the efficiency of FEVIADs which take into account the different sources of power loss.

In this respect, two papers were published in the same year, based on simulations. Parker et al. [26] showed that redistributing the front/back torque split yields the greatest power savings, while additional efficiency can be achieved, in corners, by redirecting torque towards the pair of wheels that are external to the curve. This was found by studying the vertical loads on the wheels, the friction ellipse and the load transfers due to both longitudinal acceleration variations during cornering maneuvers. This work got to the important conclusion that it is desirable to allocate more torque in correspondence to greater normal loads, generating tire forces with less tire slip (beneficial not only for energy efficiency but also for vehicle handling and stability). Zhang et al. [27] published a similar study considering only the front-to-rear distribution but taking into account different values of the friction coefficient and using a fuzzy-rule-based method to calculate the front-to-rear distribution coefficient.

Lin and Xu [28] developed and simulated a vehicle control strategy to allow optimal torque distribution in terms of vehicle motion control and energy savings under combined conditions of acceleration and cornering. The proposed approach was based on a hierarchical structure: at the high-level the desired driving torque and yaw moment were calculated using sliding mode control, and at the low-level the total driving torque was allocated to the wheels by means of a multi-objective optimization. A slip ratio-based constraint was added to the penalty function. The multi-objective programming was solved based on a combination of off-line and on-line optimization algorithms.

Still in 2015, Fujimoto and Harada [6] created a FEVIAD prototype with four in-wheel motors (Figure 7), and conducted several experimental tests. All the data obtained focused only on the longitudinal dynamics, where the optimal distribution depends solely on vehicle acceleration and velocity. Even so, the CA strategy was optimized and validated both in traction and braking mode. The simulation and experimental results confirmed the effectiveness of the proposed system, and the simulation and bench test results on the energy consumption matched the field test results.

Figure 7. The FEVIAD prototype developed in-house proposed by Fujimoto and Harada (reproduced from [6]).

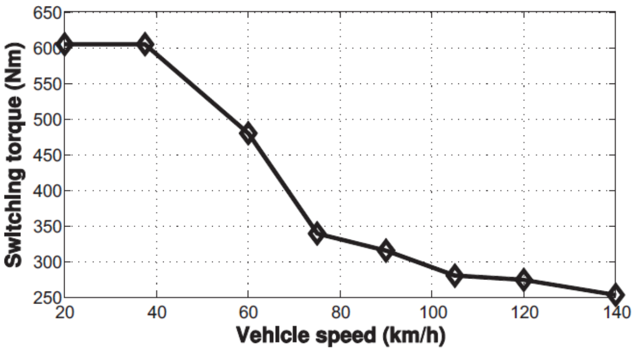

Figure 8. Switching torque for each side of the vehicle as a function of velocity (reproduced from [12]).

In 2016 Dizqah et al. [12] provided a noteworthy contribution, by formulating a novel mathematical analysis of the CA problem, including the concept of switching torque. The paper showed that, given a generic overall force demand and yaw moment demand, the torque demand of each vehicle side can be computed independently. Then, the CA problem reduces to the optimal allocation of the torque at each vehicle side between the front and rear axles. The switching torque is a speed-dependent value of torque demand at which the power loss of the even distribution strategy is equal to the one of the single-axle strategy. For torque demands lower than the switching torque, the single-axle strategy is more convenient. Conversely, the even distribution is better for torque demands higher than the switching torque. As a result, the optimal CA of the vehicle is achieved by using either the single axle or even distribution strategies, depending on torque demand and vehicle speed. The switching torque values (Figure 8) were stored as a look-up table in the controller. In terms of implementation on the vehicle, the developed procedure can easily be run in real time on hardware with low-computational processing power. The proposed CA was validated by means of tests on a rolling road facility with an electric Range Rover Evoque prototype featuring 4 onboard drivetrains, transmissions and half-shafts.

Gruber et al. [29] used the same vehicle prototype (Figure 9) to present several experimental results obtained on the rolling road and on proving grounds. This study confirmed the extent of benefits achievable using torque-vectoring in terms of vehicle dynamics behaviour and vehicle energy efficiency. Interesting considerations were made regarding the torque-vectoring-based design of the vehicle understeer characteristic. Differently from other contributions, the vehicle understeer characteristic was purposely designed for maximising energy efficiency [30][31]. As a result, the optimal understeer characteristic in terms of energy efficiency resulted to be close to the condition of neutral steering for the specific electric vehicle.

In 2016, Baumann et al. [32] published a paper featuring a motorbike prototype with one electric motor per wheel (Figure 10). The electric motor installed in the front wheel allows a significant regeneration, since most of the braking force is usually applied on the front wheel. This offers the advantage of non-wearing braking. Information on the vehicle states was acquired from appropriate sensors and a Kalman filter. The introduced torque distribution strategy splits the torque based on the motors efficiency map. A model predictive control algorithm to reduce undesired brake steer torque (which is generated when braking while cornering) was also presented. A traction control protocol to increase safety was presented and discussed, based on the observation of the wheel angular accelerations.

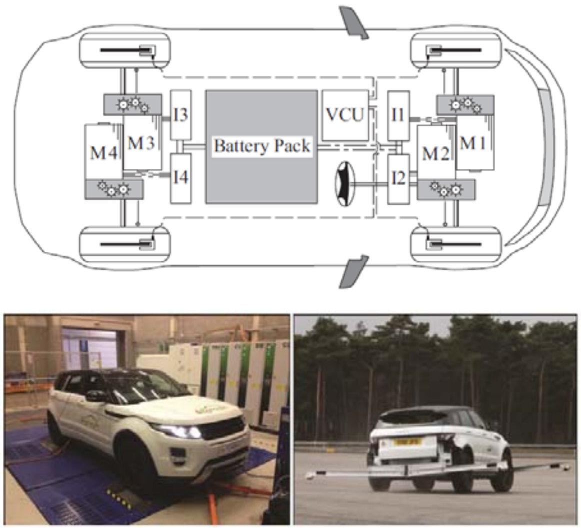

Figure 9. Experimental testing of the prototype Range Rover Evoque (on the rolling road and on the proving ground) and its body architecture (reproduced from [29]).

Figure 10. The all-wheel drive motorbike and its suspension fork (reproduced from [32]).

In 2017, Lenzo et al. [24] continued the work presented in [12] with a more detailed study based on data collected from the Range Rover Evoque FEVIAD. The paper discussed novel computationally efficient torque distribution strategies aimed at minimizing overall power loss while providing the required level of overall force and yaw moment. Analytical solutions of the torque control allocation problem were derived and effects of load transfers due to driving/braking and cornering were studied and discussed in detail. The results of an analytically derived algorithm were contrasted with those from two other control allocation strategies, based on the offline numerical solution of more detailed formulations of the control allocation problem (i.e., a multi-parametric nonlinear programming, mp-NLP problem). The experiments showed that the computationally efficient algorithms represent a very good compromise between low energy consumption and controller complexity. In fact, for all driving cycles the proposed CA strategies led to reduced energy consumption compared to both the single-axle and even distribution strategies. It was also confirmed that a fitting model based on a cubic polynomial is a good approximation of the measured drivetrain power loss characteristic as a function of the torque demand.

In the same year two more papers dealt with noteworthy topics, yet presenting only simulation results. Koehler et al. [33] proposed a heuristic algorithm that, based on the value of longitudinal and lateral accelerations, decides whether to implement torque-vectoring to either save energy or to enhance the stability and safety of the vehicle. Essentially they presented a novel torque-vectoring control system that improves both vehicle dynamics and energy efficiency. The CA strategy takes all the most important parameters into account, such as tire slip, understeer gradient, front/rear and left/right distribution coefficients and load transfers (Figure 11).

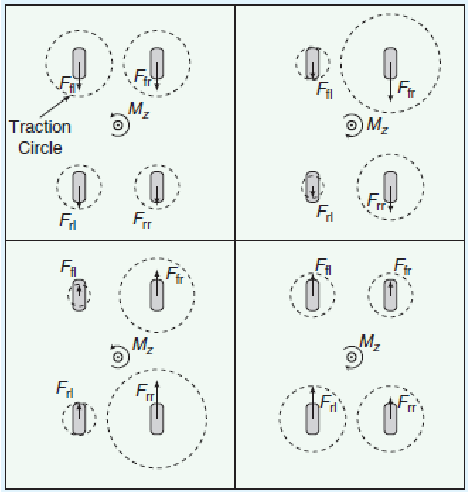

Figure 11. Illustration of the forces created by the electric machines at each wheel and their traction circle for the different maneuver steps (reproduced from [33]).

Wang et al. [2] investigated the optimal component sizing problem for a FEVIAD. A real-time optimal distribution strategy was devised to allocate the torque demands to each in-wheel motor of the vehicle with the aim to make them work in high-efficiency areas as much as possible. Particle swarm optimization (PSO) was employed to search for the optimal sizing solution. Simulation results showed that the proposed PSO-based optimization method, combined with the real-time torque distribution strategy, can effectively downsize the main powertrain components and lead to lower energy consumption.

4 THE MOST RECENT STUDIES: 2018-2019

At the beginning of 2018, Hua et al. [34] proposed a hierarchical control method that uses sliding mode control (SMC) to calculate the total desired force and yaw moment. The paper addresses the energy optimization problem by employing a sequence quadratic programming (SQP) scheme to reduce the complexity of the optimization algorithm, and to provide optimally distributed in-wheel motor torques. The study also pointed out the importance of including tire slip in the power loss computation, since the sole reduction in motor power loss is not enough to have an impact on the overall power utilization.

This suggestion was not considered by Zhang and Zhai, who did not take tire slip into account. Zhang et al. [35] focused mainly on braking safety and on braking regeneration, to maximise braking stability and recapture as much of the braking energy as possible. The simulated changeable distribution of braking torque was obtained based on the ideal front-rear braking force distribution curve, while complying with braking regulations from the Economic Commission for Europe. The vehicle was driven by four independent motors and a clutch between each motor and its gearbox (Figure 12). It was then possible to engagedisengage different drivetrains and improve efficiency depending on driving conditions, both in traction and regeneration.

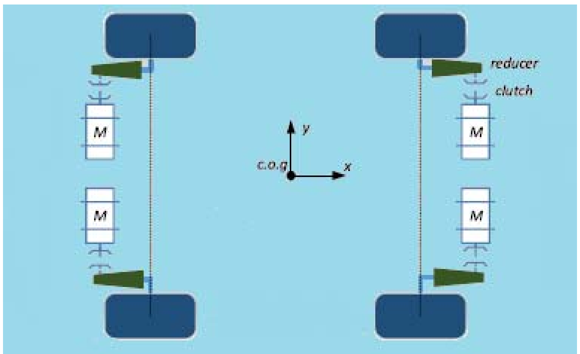

Figure 12. The vehicle model proposed by Zhang et al. (reproduced from [35]).

Zhai et al. [36] presented an adaptive two-hierarchy torque distribution algorithm to improve both stability and energy saving, preceded by a fuzzy PID upper-level controller that works continuously during steering maneuvers to maintain the integrated control of the yaw rate and the sideslip angle. The simulations results showed that this controller can reduce energy consumption and improve vehicle steering stability even on roads with a low friction coefficient.

Chen et al. [5] proposed a model predictive control (MPC) torque distribution strategy to improve the vehicle stability and the drivetrain energy efficiency. A simple vehicle dynamic model was developed to calculate the desired vehicle states and yaw moment, which are used as the reference signals in the MPC controller. The results indicated that the proposed strategy can improve the vehicle handing performances by controlling sideslip angle and yaw rate and it can reduce energy consumption with respect to distribution strategies based on the sole vertical load. The vertical load distribution is also the rationale used in Parra et al. [37], where an intelligent torque-vectoring controller is described. The vertical loads are obtained through a neuro-fuzzy estimator.

A study by De Filippis et al. [38] presented an integrated approach based on a combination of recent techniques and new experimental results. It demonstrated that significant reductions in energy consumption can be achieved by combining an appropriate tuning of the reference understeer characteristic and a CA strategy. The analysis demonstrated that, when considering only the drivetrain power losses, multiple equivalent solutions exist. This was supported by analytical solutions, based on a third order polynomial approximation of the drivetrain power losses, as in [24]. In practice, it turned out that only one solution represent an absolute minimum in terms of power losses, due to the tire slip power losses. This was supported by experimental results from a Range Rover Evoque FEVIAD which showed that the power consumption was minimized for a specific destabilizing yaw moment, function of the operating conditions of the vehicle. At the same lateral acceleration, the power consumption characteristic also exhibited a local minimum for a stabilizing yaw moment, approximately at the same absolute value as the optimal destabilizing yaw moment (Figure 13). Tire slip power loss can be used for the selection of the best solution among the many solutions of the algorithm minimizing the electric drivetrain power loss. This led to the formulation and experimental validation of a rule-based sub-optimal torque-vectoring control strategy to reduce the total power consumption.

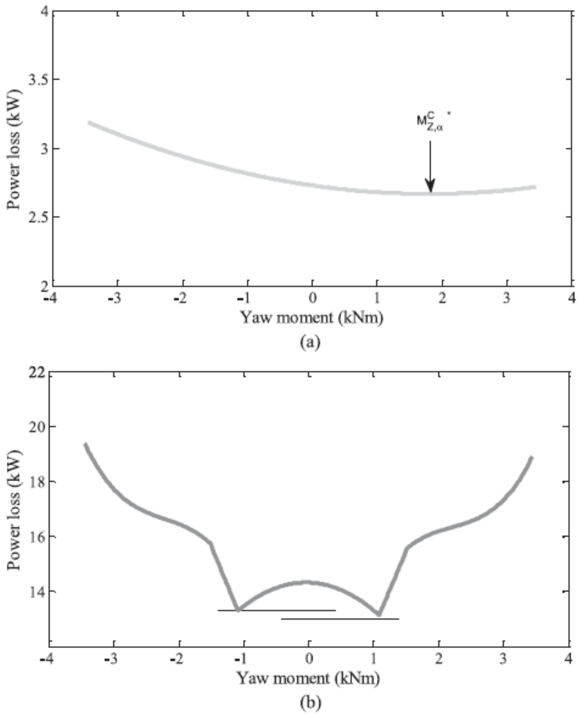

Figure 13. (a) Tire slip power loss and (b) total power loss as a function of the yaw moment at V=60 km/h, a_X=0.5 m/s^2 and a_Y=4 m/s^2 (reproduced from [38]).

Despite most studies focused on passenger cars, the recent literature also presents interesting studies on other types of vehicles. Liu et al. [39] developed an integrated control framework consisting of a basic chassis control and a torque-vectoring control aimed at improving the motion control performances of a novel three-axle electric bus (Figure 14). The bus is driven by four identical hub motors integrated with gear reducers on two rear axles, one of which with active steering capability. The torque-vectoring control was based on the holistic cornering control method, by which a torque increment is generated to change the motion states of the vehicle. A constrained quadratic programming problem was formulated for real-time optimization, with constraints related to the anti-wheel-slip requirements and physical limits. Different test cases were simulated through different driving cycles. The results showed satisfactory energy savings, improved tire-wear index, and enhanced safety and stability of the bus.

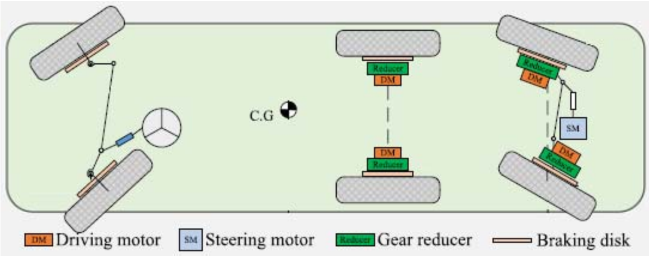

Figure 14. The vehicle body structure proposed by Liu et al. (reproduced from [39]).

Hu et al. [40] presented another study on an electric bus, combining power-source sizing and energy management optimization. A novel convex programming-based approach was developed, that enabled a quick, effective optimization of energy management strategy, battery dimension and motor dimension for a dual-motor electric bus. The model features a clutch at the rear axle so as to disengage one of the two motors depending on the operating conditions (Figure 15). Several simulation results confirmed that the proposed approach can optimize energy efficiency with an appropriate trade off in the design phase, concerning the size of the battery, the size of the two motors, and the power flow control.

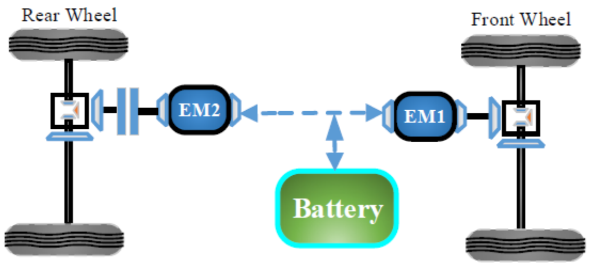

Figure 15. The vehicle model proposed by Hu et al. (reproduced from [40]).

In early 2019 Han et al. [41] presented a CA strategy to improve the efficiency of EVs using a new type of actuators, the Modular Cascade Machines (MCM). A MCM system is a composed of multiple machines working in cascade (Figure 16). All unit machines share one shaft and one shell, with benefits in terms of overall size and weight as well as power density. Each unit machine may have different characteristics and is controlled by an independent inverter. All inverters are operated by a controller and a vehicle management system, making the MCM system suitable to propel electric vehicles. The overall MCM system efficiency depends on the unit machines themselves and on the torque distribution strategy. Aiming at maximizing the overall efficiency of the system, each unit machine is controlled to work in its own high-efficiency region as much as possible. It should be noted, however, that this type of actuator is still under development and testing.

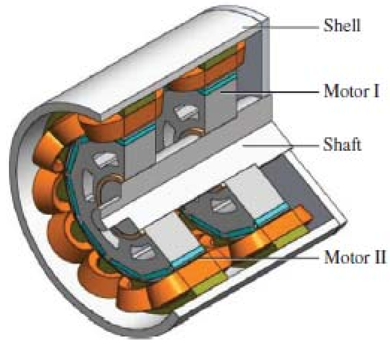

Figure 16. Structure of the modular cascade machines (reproduced from [41]).

5 CATEGORIZATION AND FUTURE PERSPECTIVES

Table 1 provides an overview of the papers discussed so far, in chronological order. The most relevant categorization parameters were chosen as follows:

- *Vehicle configuration*: type and number of drivetrains/in-wheel motors.
- *Driving mode(s)*: traction, regeneration, or both.
- *Simulations/Experiments*: which one is considered - in some cases, both.
- *Understeer characteristic*: whether it is taken into account within the CA strategy.
- *Losses considered*: which sources of energy dissipation are taken into account.
- *Dynamics considered*: longitudinal dynamics, lateral dynamics, or both.
- *Driving Cycles/Maneuvers:* which maneuvers or driving cycles were performed to test and demonstrate the effectiveness of the proposed CA strategy.
- *Peculiarities*: the most relevant contribution or result shown by the study.

In light of the literature review presented, this section identifies and discusses areas to be targeted in future research.

Important points to be accounted for in modelling are:

- to include the possibility of working both in traction and in regeneration, with an appropriate characterization of the actuator efficiency in both conditions - e.g. [13] arbitrarily assumes that the efficiency in regeneration is 1.1 times the one in traction, or [12] characterizes the efficiency in traction assuming it to be the same in regeneration;

- to take into account not only longitudinal dynamics, but also lateral dynamics including all related effects, including the understeer characteristic, as that can lead to energy savings greater than the ones obtained via optimal front-rear wheel torque distribution [31];

- to consider load transfers and their effects on the longitudinal slip power losses and on vehicle handling and stability [24] [26] [37];

- to consider all the possible sources of power loss, as their relative contribution to the overall vehicle power losses can significantly change depending on the driving conditions - focussing only on the drivetrain power losses can be misleading [25] [38].

Although the improvement of energy performance is fundamental, vehicle safety and drivability come first. CA strategies should be designed to provide the most energy-efficient torque distribution in all normal driving situations, without hindering the possibility of controlling the vehicle in safety-critical conditions. In this respect, future vehicle control strategies would benefit from appropriate vehicle dynamic state estimators, which can also be exploited in CA strategies. Research in the field of state estimation is very active, as to date there is no ultimate solution regarding the estimation of states such as vehicle longitudinal and lateral velocities, tire slips, tire-road forces or friction coefficient [42] [43] [44] [45] [46], which are often required in existing CA schemes [6] [12] [25] [32] [39] [47].

As already suggested in [25], there could be more than one CA strategy for the vehicle (ideally coupled with a proper understeer characteristic), selectable by the driver based on the driving situation. For certain environments or for certain types of vehicle, CA modes such as "rain" or "sport" could be considered similarly to, e.g., the existing Alfa Romeo DNA (Dynamic, Neutral, All weather) system [48].

It would also be interesting to further investigate the option of HESSs, e.g. using a supercapacitor as discussed in [11] [32] to help to extend the range and the battery life and to increase the available power density both in traction and regeneration.

Another very important point concerns driving cycles. To date there is no scientifically recognized cycle that allows comparative testing of either FEVIADs or electric vehicles in general [49]. This implies a great ambiguity in the results and makes it difficult to assess the work published since there are no common rules and evaluation parameters. Existing cycles for internal combustion engine vehicles, such as the New European Driving Cycle (NEDC), are frowned upon by part of the literature [50] [51] [52]. New driving cycles should be created [50] that take into account new developments in vehicle mechanics and the peculiarities of electric vehicles.

A further potential future development, as already investigated in [39] [40], is the implementation of CA strategies on electric heavy transport vehicles such as buses or similar electric vehicles with a pre-established route. If vehicle follows a pre-established route, the wheel torque distribution could be optimized a-priori, e.g. developing specific regenerative braking strategies by knowing in advance where the vehicle slows down or stops. Such kind of vehicles usually have large dimensions, thus allowing more space for batteries and potential supercapacitors.

Regardless of the type of vehicle considered and of the specific CA strategy, further experimental testing on vehicle prototypes would be desirable, wherever possible, compared to simulations.

6 CONCLUSION

This paper presented a global and extensive literature review on torque distribution strategies aimed at enhancing energy efficiency for fully electric vehicles with independently actuated drivetrains or in-wheel motors. After discussing the general concept, the vast majority of the solutions to the control allocation problem developed to date was analyzed. A summary table was presented showing the main comparison parameters among the various studies. Finally, future research directions are proposed, illustrating the key features that could allow further steps ahead.

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Table I - Categorization of the existing CA strategies

Paper	*Vehicle configuration*	*Driving mode(s)*	*Simulations / Experiments*	*Understeer Characteristic*	*Losses Considered*	*Dynamics considered*	*Driving Cycles / Maneuvers*	*Peculiarities*
[13]	Vehicle model with 4 in-wheel motors	Traction and Regeneration	Simulations	Not considered	Motor	Longitudinal	Straight line, different vehicle speeds	First attempt to define the switching torque
[3]	Prototype vehicle with 4 in-wheel motors	Traction and Regeneration	Experiments - Chassis Dynamometer Tests	Not considered	Motor and Rolling Resistance	Longitudinal	Straight line, different torque demands	Comparison with the two wheel drive mode and the equally distributed torque mode
[21]	Vehicle model with a front in-line motor and rear in-wheel motors	Traction and Regeneration	Simulations	Not considered	Motor, transmission and tire slip	Longitudinal and Lateral	Straight line and cornering	Driving controller consisted in three parts, vehicle model with 3 motors and strategy comparison with others 3 controllers
[4]	Prototype vehicle with 4 in-wheel motors	Traction and Regeneration	Simulations and Experiments	Not considered	Motor and inverter	Longitudinal	Straight line, different torque demands and vehicle speeds	Comparison with the two wheel drive mode and the evenly distributed torque mode, and with the measured and simulated motor efficiency
[22]	Vehicle model with 4 drivetrains	Traction	Simulations	Not considered	Motor	Longitudinal and Lateral	Straight line at different accelerations, ramp steer	Comparison of 3 different types of electric motors to find the most energy efficient one
[23]	Vehicle model with 4 drivetrains	Traction	Simulations	Considered	Motor	Longitudinal and Lateral	Straight line at different velocities, step steer, ramp steer	One of the first attempts to implement an online control allocation method with low computational costs
[11]	Vehicle model with an HESS at front axle and an ICE at rear axle	Traction and Regeneration	Simulations	Not considered	Motor, Battery, Supercapacitor and DC/DC Converter	Longitudinal	NEDC, FTP, ARTEMIS, US06 Cycles	Demonstrates the benefits of using the supercapacitors together with the battery
[20]	Vehicle model with 2 electric motors, gearbox and TV differential	Traction	Simulations	Considered	Motor, TV differential, transmission and tire slip	Longitudinal and Lateral	Straight line and cornering	First considerations on different types of power losses and on the problems of torque fluctuation
[8]	Vehicle model with 2 electric motors, gearbox and differential	Traction	Simulations and Experiments	Not considered	Motor, inverter and transmission	Longitudinal	ARTEMIS	First considerations on switching torque and clutching operations
[25]	Vehicle model with 4 drivetrains	Traction	Simulations	Considered	Battery, aerodynamic drag, rolling resistance, transmission, motor and tire slip	Longitudinal and Lateral	Straight line at different velocities, step steer, ramp steer	Comprehensive report on energy losses of EVs
[26]	Vehicle model with 4 drivetrains	Traction	Simulations	Considered	Aerodynamic drag, motor and tire slip	Longitudinal and Lateral	Straight line and cornering	Compares the effects of different centre-of-mass placements for different active drivetrains configurations (only front, only rear, even)
[6]	Prototype vehicle with 4 in-wheel motors	Traction and Regeneration	Simulations and Experiments	Not considered	Aerodynamic drag, motor and tire slip	Longitudinal and Lateral	Straight line and cornering, JC08 (Japanese driving cycle)	Results are obtained from simulated tests, bench tests and actual field tests.
[27]	Vehicle model with 4 in-wheel motors	Traction	Simulations	Not considered	Motor and tire slip	Longitudinal and Lateral	NEDC	Two objective functions for stability and energy saving connected by the sideslip angle
[28]	Vehicle model with 4 drivetrains	Traction	Simulations	Not considered	Drivetrain and tire slip	Longitudinal and Lateral	Straight line and cornering	Multi-objective hierarchical optimization based on a combination of off-line and on-line CA algorithm

[12]	Prototype vehicle with 4 drivetrains	Traction and Regeneration	Simulations and Experiments	Not considered	Drivetrain, rolling resistance and tire slip	Longitudinal and Lateral	NEDC, ARTEMIS and EUDC 8% slope	Analytical definition of Switching Torque via experimental measurement of drivetrain efficiency
[29]	Prototype Range Rover Evoque with 4 drivetrains	Traction	Experiments	Considered	Drivetrain, rolling resistance and tire slip	Longitudinal and Lateral	NEDC, SDDC and EUDC 8% slope	Excellent summary about torque-vectoring, CA algorithms, understeer characteristics and energy efficiency, all demonstrated with a prototype vehicle
[33]	Vehicle model with 4 drivetrains	Traction and Regeneration	Simulations	Considered	Drivetrain and tire slip	Longitudinal and Lateral	Steady state circular driving, manual curve driving, Hockenheim racing circuit and ARTEMIS cycle	Heuristic method for optimized torque distribution (stability and energy saving)
[32]	Prototype motorcycle with 2 in-wheel motors	Traction and Regeneration	Simulations and Experiments	Not provided	Motor	Longitudinal and Lateral	Straight line and cornering	CA strategy for an all-wheel drive motorbike which improves both safety and energy efficiency
[2]	Vehicle model with 4 in-wheel motors	Traction and Regeneration	Simulations	Not considered	Motor and battery	Longitudinal	NEDC	Downsizing of the main powertrain components via Particle Swarm Algorithm
[24]	Prototype vehicle with 4 drivetrains	Traction and Regeneration	Simulations and Experiments	Not considered	Drivetrain, rolling resistance and tire slip	Longitudinal and Lateral	NEDC, SDDC, ARTEMIS and EUDC 8% slope	Hybrid Control Allocation Algorithm
[5]	Vehicle model with 4 drivetrains	Traction	Simulations	Not considered	Drivetrain	Longitudinal and Lateral	Sine steer, step steer	A model predictive control based torque distribution strategy, with a 2-DoF vehicle dynamic model
[39]	Bus model with 3 axles	Traction and Regeneration	Simulations	Not considered	Not explicitly mentioned	Longitudinal and Lateral	NEDC, UDDS, HWEFT	CA strategy for a three-axle electric bus with distributed motor-driven and active rear steering subsystem to improve stability and energy efficiency.
[34]	Vehicle model with 4 in-wheel motors	Traction and Regeneration	Simulations	Not considered	Motor, rolling resistance and tire slip	Longitudinal and Lateral	Ramp steer, NEDC and UDDS	Emphasizes the importance of including the tire slip in the power losses to improve energy saving
[35]	Vehicle model with 4 drivetrains	Traction and Regeneration	Simulations	Not considered	Drivetrain	Longitudinal	NEDC	Particular attention to braking regeneration
[36]	Vehicle model with 4 in-wheel motors	Traction	Simulations	Not considered	Not explicitly mentioned	Longitudinal and Lateral	Step steer, double-lane-change	Adaptive two-hierarchy torque distribution (stability and energy saving) with a continuous yaw moment controller
[38]	Prototype vehicle with 4 drivetrains	Traction and Regeneration	Simulations and Experiments	Considered	Drivetrain, rolling resistance and tire slip	Longitudinal and Lateral	Cornering, skid-pad	CA strategy with a yaw moment based sub optimal solution to improve energy efficiency and drivability
[40]	Bus model with 2 drivetrains	Traction and Regeneration	Simulations	Not considered	Motor, battery, aerodynamic drag, rolling resistance and transmission	Longitudinal and Lateral	Gothenburg, FTP and CSC	Sizing of battery and motors of an electric bus with 2 drivetrains and at the same time a CA strategy to improve energy efficiency