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On the enhancement of vehicle handling and energy efficiency of electric vehicles with multiple motors: the iCOMPOSE project

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Abstract. Electric vehicles with multiple motors allow torque-vectoring, i.e., the individual control of each powertrain torque. Torque-vectoring (TV) can provide: i) enhancement of vehicle safety and handling, via the generation of a direct yaw moment to shape the understeer characteristics and increase yaw and sideslip damping; and ii) energy consumption reductions, via appropriate torque allocation to each motor. The FP7 European project iCOMPOSE thoroughly addressed i) and ii). Theoretical analyses were carried out to design state-of-the-art TV controllers, which were validated through: a) vehicle simulations; and b) extensive experimental tests, which were performed at rolling road facilities and proving grounds, using a Range Rover Evoque prototype equipped with four identical on-board electric powertrains. This paper provides an overview of the TV-related contributions of iCOMPOSE.

Keywords: Torque-vectoring; vehicle dynamics; yaw rate control; sideslip angle control; hitch angle control; energy efficiency; experiments.

1 Introduction

Torque-vectoring (TV) is a typical feature of electric vehicles (EVs) with multiple motors. TV is based on the individual and continuous control of each powertrain torque. This allows different torque levels on the left- and right-hand sides of the vehicle, which generates a direct yaw moment and can enhance vehicle safety and handling. Moreover, appropriate reference yaw rate formulations and torque allocation strategies can reduce vehicle power losses, and thus energy consumption.

These topics were partially addressed in the FP7 European E-VECTOORC project [1], with results such as those in [2]. The follow-up FP7 European iCOMPOSE project [3] extended the findings of E-VECTOORC on vehicle safety and handling, and thoroughly investigated TV techniques for energy efficiency enhancement. Theoretical analyses were carried out through vehicle simulations with Matlab-Simulink and IPG CarMaker. The developed controllers were assessed via extensive experimental tests at rolling road facilities and proving grounds, using a Range Rover Evoque prototype equipped with four identical on-board electric powertrains (Fig. 1).

The remainder of the paper is structured as follows: Section 2 deals with the enhancement of vehicle safety and handling; Section 3 discusses the energy efficiency activities; and Section 4 summarizes the main conclusions.

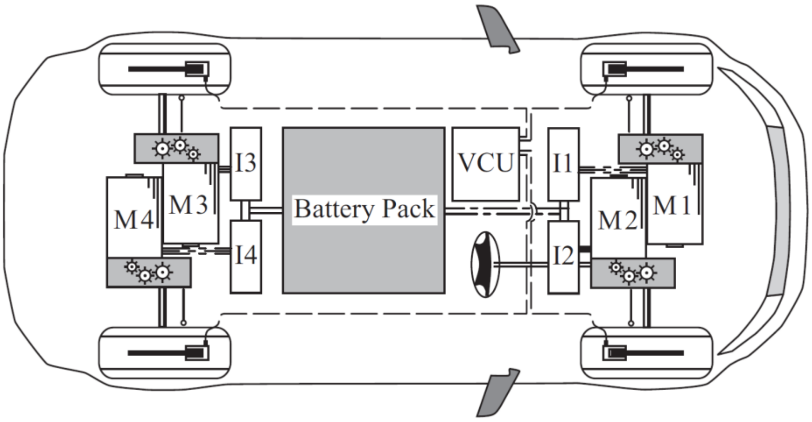

Fig. 1. Schematic of the architecture of the Range Rover Evoque demonstrator. M1-M4 = switched reluctance motors; I1-I4 = inverters; VCU = vehicle control unit (reproduced from [4]).

2 Enhancement of vehicle safety and handling

TV can enhance the handling qualities of a vehicle well beyond the capabilities of current conventional stability control systems based on the actuation of the friction brakes. Compared to these systems, the TV interventions can be seamless and continuous, without variation of the net longitudinal force, unless critical conditions requiring torque demand reductions are identified.

TV-based yaw rate controllers usually require accurate estimation of the tire-road friction coefficient, which is still a challenging problem. To alleviate this issue, the study in [5] developed a Single-Input-Single-Output (SISO) formulation to control yaw rate and sideslip angle, in which the reference yaw rate is modified if the estimated sideslip angle exceeds predetermined thresholds. If the sideslip angle is below a critical value, the vehicle conditions are deemed safe and the reference yaw rate just follows the handling requirements, such as those in [2]. Simulations and experiments showed safe and consistent performance in variable friction conditions. For example, Fig. 2 refers to a slalom maneuver on a slippery surface without (left) and with (right) sideslip-based TV control. Another recommendation of [5] is that the sideslip-related variation of the reference yaw rate should be based on the dynamic contribution of the sideslip angle, which coincides with the rear axle sideslip angle for a vehicle without rear-wheel-steering capability.

Fig. 2. The iCOMPOSE electric vehicle demonstrator performing a slalom test on a slippery road: (left) without controller; (right) with controller (reproduced from [5]).

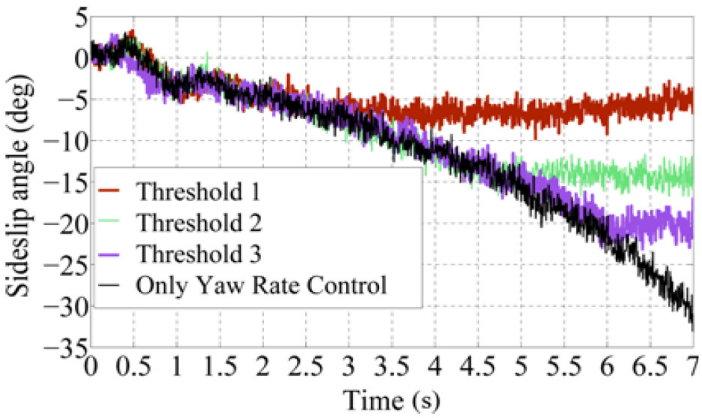

Fig. 3. Vehicle sideslip angle control during step steer tests (reproduced from [7]).

Fig. 4. The iCOMPOSE electric vehicle demonstrator towing a passive trailer.

A possibility offered by the concurrent control of yaw rate and sideslip angle is the implementation of drift control modes, which facilitate the generation of a desired significant level of sideslip angle, and then allow the vehicle to persistently operate in such conditions (Fig. 3) [6-7].

A similar approach, based on a SISO formulation and a correction of the reference yaw rate in critical scenarios, was developed for the feedback control of the hitch angle when the TV controlled vehicle tows a trailer (Fig. 4) [8]. The hitch angle controller prevents trailer oscillations and instability during extreme cornering maneuvers through the TV actuation only on the towing vehicle. iCOMPOSE developed and tested a simple proportional integral (PI) controller with gain scheduling on vehicle speed. Sinusoidal steer test results showed that the proposed algorithm significantly improves the cornering stability and active safety of the articulated vehicle.

Although in principle any feedback controller can be used to generate the reference direct yaw moment based on the yaw rate error, different control structures lead to different performance levels. iCOMPOSE studied and objectively compared a range of feedback direct yaw moment controllers, including H_∞ loop-shaping, integral sliding mode [7] and robust linear quadratic regulator [9] formulations.

During iCOMPOSE, the availability of an electric vehicle demonstrator with four independent motors allowed emulating different vehicle architectures, e.g., All-Wheel-Drive (AWD), Front-Wheel-Drive (FWD) and Rear-Wheel-Drive (RWD), on the same vehicle hardware, just by changing the vehicle control settings. This led to a detailed assessment of the effect of the front-to-rear torque distribution on the handling behavior in absence of direct yaw moment [10], which highlighted an apparently surprising result: at low speeds and high values of lateral acceleration, the RWD architecture is more understeering (Fig. 5) than the FWD and AWD ones. The result was justified through the analysis of the yaw moment contributions caused by the longitudinal forces of the front tires.

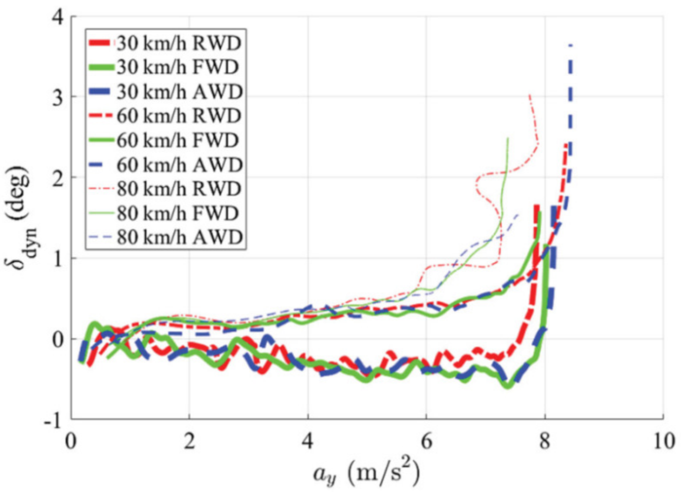

Fig. 5. Dynamic steering angle as a function of the lateral acceleration of the vehicle (reproduced from [10]).

3 Enhancement of energy efficiency

The drivetrain power losses of the iCOMPOSE vehicle demonstrator were experimentally characterized on a MAHA rolling road facility (Fig. 6). Based on the measured power losses, effective wheel torque control allocation (CA) strategies were developed to reduce drivetrain and tire slip power losses [11].

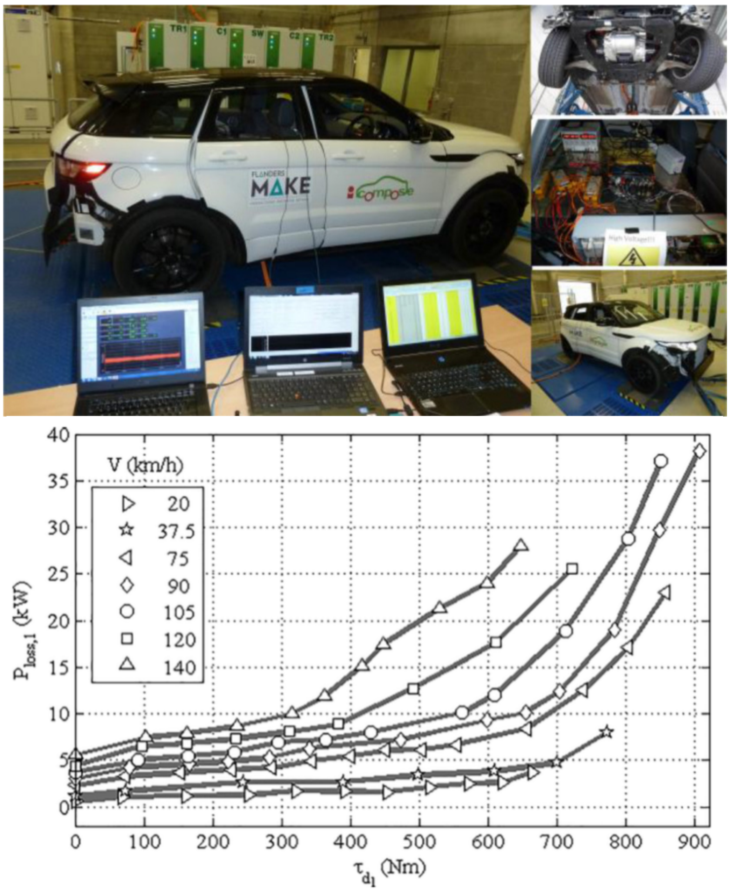

Fig. 6. (top) The iCOMPOSE electric vehicle demonstrator setup on the rolling road facility (reproduced from [12]); (bottom) Measured drivetrain power losses as functions of vehicle torque demand and speed (reproduced from [11]).

More specifically, starting from the total torque demand and reference direct yaw moment, the CA strategies calculate the required torque for each vehicle side, and distribute the side torque to the front and rear motors to obtain the optimal front-to-rear distribution for the specific condition. Alternative methods were evaluated for such calculation: i) numerical methods, based on the direct interpolation of the experimental power loss data; ii) analytical methods, based on interpolating functions to approximate the power loss characteristics; and iii) look-up table based methods, achieving a hybrid solution between i) and ii). The techniques associated with i), ii) and iii) are referred to as Implicit CA (I-CA), Explicit CA (E-CA), and Hybrid CA (H-CA) in [11]. iii) was shown to provide the best balance between online computational burden, offline calculations, high energy efficiency, and driving comfort

[11,12]. In particular, the H-CA and the E-CA define the so-called "switching torque", i.e., a speed-dependent value of side torque demand. For side torque demands below the switching torque, it is more convenient to use a single motor within that side. When the torque demand exceeds the switching torque, an even distribution among front and rear motors within the same vehicle side is the best option. The proposed energy-efficient CA strategies brought typical energy savings of 2%-3% along conventional driving cycles, and up to ~5% during cornering, with respect to fixed torque distribution algorithms.

Another important result of iCOMPOSE was the energy consumption reduction achieved through the design of the reference cornering response of the vehicle, i.e., the reference understeer characteristic. Experimental skidpad tests were carried out for different understeer characteristics, achieved through TV actuation [14]. For the case study vehicle, it was found that the optimal cornering response in terms of energy efficiency is close to the neutral steering condition, and can reduce the measured inverter input power by >10% (Fig. 7).

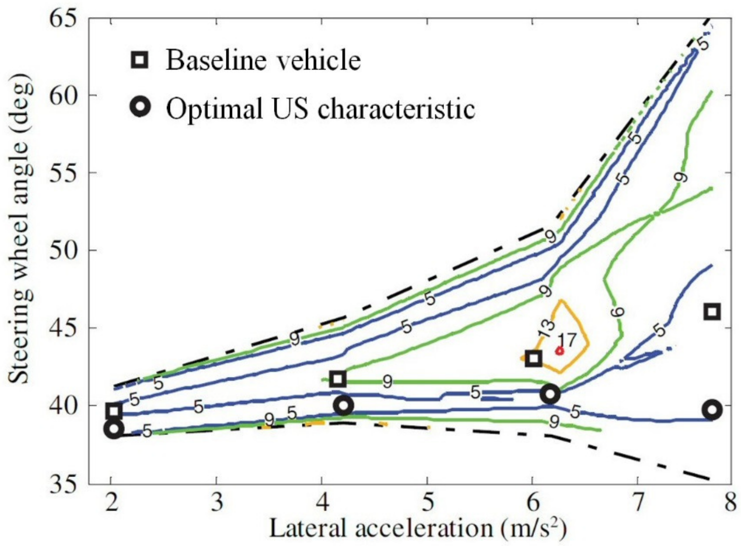

Fig. 7. Understeer diagram with indication of the relative power input increase (in percentage) w.r.t. the optimal understeer characteristic (reproduced from [13]).

The energy efficiency improvements obtained through the optimal design of the vehicle cornering response, and those obtained through the optimal CA algorithms, were combined in [15], which presents a theoretical approach based on a cubic approximation of the drivetrain power losses as functions of torque demand. The analysis demonstrates that, when considering only the drivetrain power losses, multiple equivalent optimal values of the reference direct yaw moment exist. These imply the progressive activation of an increasing number of electric powertrains, as a function of the absolute value of the total longitudinal force demand. However, when taking into account the effect of tire slip, only one solution provides an absolute minimum in terms of total power losses (Fig. 8). This was supported by experimental results from the Range Rover Evoque demonstrator, which showed that the power consumption was minimized for a specific destabilizing direct yaw moment, function of the operating conditions of the vehicle. For a given lateral acceleration, the experimental power consumption characteristics also exhibited a local minimum for a stabilizing yaw moment, approximately at the same absolute value as the optimal destabilizing yaw moment. This led to the formulation of a rule-based sub-optimal TV control strategy, taking into account tire slip power losses to select the best solution among the multiple ones from the powertrain-based algorithm. The effectiveness of the strategy was experimentally validated in specific steady-state cornering conditions, leading to energy savings >8% with respect to the baseline vehicle.

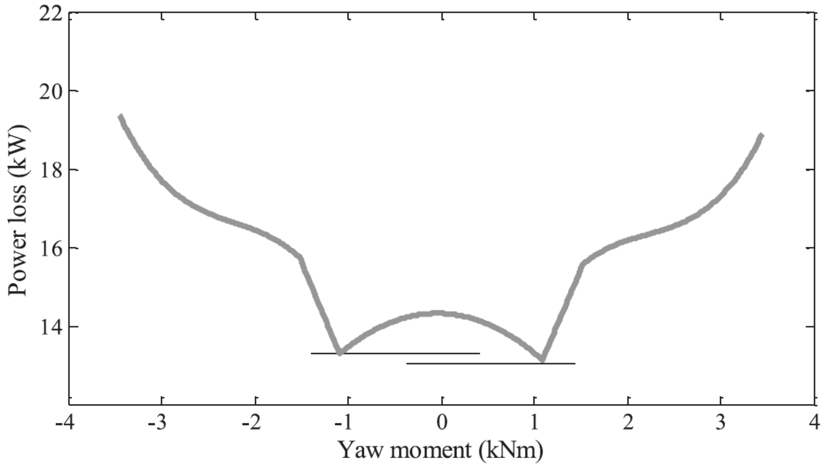

Fig. 8. Estimated power loss as a function of the direct yaw moment at 60 km/h, with a longitudinal acceleration of 0.5 m/s^2 and a lateral acceleration of 4 m/s^2. The absolute minimum is for a destabilizing yaw moment, because of the lateral tire slip power loss contribution (reproduced from [15]).

4 Conclusions

The iCOMPOSE project provided significant contributions to the state-of-the-art of torque-vectoring control for the enhancement of vehicle handling and energy efficiency in electric vehicles with multiple motors. The iCOMPOSE results will contribute to the large scale adoption of these electric vehicle configurations.

References

1. https://cordis.europa.eu/project/rcn/99412_en.html, last accessed on 17 December 2018
2. De Novellis, L, Sorniotti, A., Gruber, P., Driving Modes for Designing the Cornering Response of Fully Electric Vehicles with Multiple Motors, Mechanical Systems and Signal Processing, 64, 1-15 (2015)
3. www.i-compose.eu, last accessed on 17 December 2018

4. Gruber, P., Sorniotti, A., Lenzo, B., De Filippis, G., Fallah, S., Energy Efficient Torque Vectoring Control, 13th International Symposium on Advanced Vehicle Control, AVEC '16, Munich, Germany (2016)
5. Lenzo, B., Sorniotti, A., Gruber, P., Sannen, K., On the Experimental Analysis of Single Input Single Output Control of Yaw Rate and Sideslip Angle, International Journal of Automotive Technology, 18:5, 799-811(2017)
6. Lenzo, B., Sorniotti, A., Gruber, P., A SISO Formulation for Yaw Rate and Sideslip Angle Control via Torque Vectoring, 14th International Symposium on Advanced Vehicle Control, AVEC '18, Beijing, China (2018)
7. Tota, A., Lenzo, B., Lu, Q., Sorniotti, A., Gruber, P., Fallah, S., Velardocchia, M., Galvagno, E., De Smet, J., On the Experimental Analysis of Integral Sliding Modes for Yaw Rate and Sideslip Control, International Journal of Automotive Technology, 19:5, 811-823 (2018)
8. Zanchetta, M., Tavernini, D., Sorniotti, A., Gruber, P., Lenzo, B., Ferrara, A., De Nijs, W., Sannen, K., De Smet, J., On the Feedback Control of Hitch Angle through Torque-Vectoring, IEEE 15th International Workshop on Advanced Motion Control, Tokyo, Japan (2018)
9. Wang, Z., Montanaro, U., Fallah, S., Sorniotti, A., Lenzo, B., A Gain Scheduled Robust Linear Quadratic Regulator for Vehicle Direct Yaw Moment Control, Mechatronics, 51, 31-45 (2018)
10. Lenzo, B., Bucchi, F., Sorniotti, A., Frendo, F., On the Handling Performance of a Vehicle with Different Front-to-Rear Wheel Torque Distributions, Vehicle System Dynamics (2018, in press)
11. Lenzo, B., De Filippis, G., Dizqah, A.M., Sorniotti, A., Gruber, P. Fallah, S., De Nijs, W., Torque Distribution Strategies for Energy-Efficient Electric Vehicles with Multiple Drivetrains, ASME Journal of Dynamic Systems, Measurement and Control, 139:12 (2017)
12. Dizqah, A.M., Lenzo, B., Sorniotti, A., Gruber, P., Fallah, S., De Smet, J., A Fast and Parametric Torque Distribution Strategy for Four-Wheel-Drive Energy-Efficient Electric Vehicles, IEEE Transactions on Industrial Electronics, 63:7, 4367-4376 (2016)
13. De Filippis, G., Lenzo, B., Sorniotti, A., Gruber, P., Sannen, K., De Smet, J., On the Energy Efficiency of Electric Vehicles with Multiple Motors, IEEE 13th Vehicle Power and Propulsion Conference (VPPC), Hangzhou, China (2016)
14. Lenzo, B., De Filippis, G., Sorniotti, A., Gruber, P., Understeer Characteristics for Energy-Efficient Fully Electric Vehicles with Multiple Motors, World Electric Vehicle Symposium (EVS29), Montreal, Canada (2016)
15. De Filippis, G., Lenzo, B., Sorniotti, A., Gruber, P., De Nijs, W., Energy-Efficient Torque-Vectoring Control of Electric Vehicles with Multiple Drivetrains, IEEE Transactions on Vehicular Technology, 67:6, 4702-4715 (2018)