Torque-vectoring control for fully electric vehicles

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16th April 2013
Vehicle Dynamics and Control 2013
Murray Edwards College, Cambridge, UK

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Presentation outline

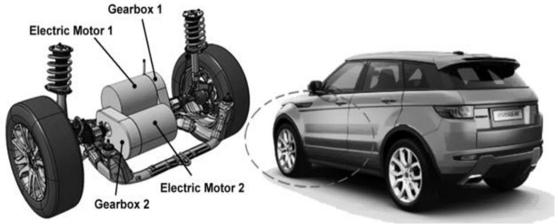
1. The E-VECTOORC project
2. The objectives of the E-VECTOORC torque-vectoring controller
3. The E-VECTOORC control structure
4. The comparison of the cost functions for wheel torque allocation
5. Results
6. Conclusions

1. The E-VECTOORC project

E-VECTOORC Consortium

Vehicle Concept and Layout	Powertrain Design and Safety	Brake Design and EM-compatibility	Vehicle Dynamics and Control
JAGUAR LAND-ROVER	inverto	TRW	UNIVERSITY OF SURREY
ŠKODA AUTO	FLANDERS' DRIVE	ita	TECHNISCHE UNIVERSITÄT ILMENAU
		cidaut	virtual vehicle

The FP7 E-VECTOORC (Electric-Vehicle Control of Individual Wheel Torque for On- and Off-Road Conditions) project brings together 11 complementary partners from industrial and research backgrounds



Key objectives:

- Development of yaw rate and sideslip angle control algorithms based on torque-vectoring to improve the vehicle dynamics performance of fully electric vehicles with multiple (from 2 to 4) individually controlled drivetrains
- Development of novel strategies of torque modulation to enhance brake energy recuperation, ABS and TC functions

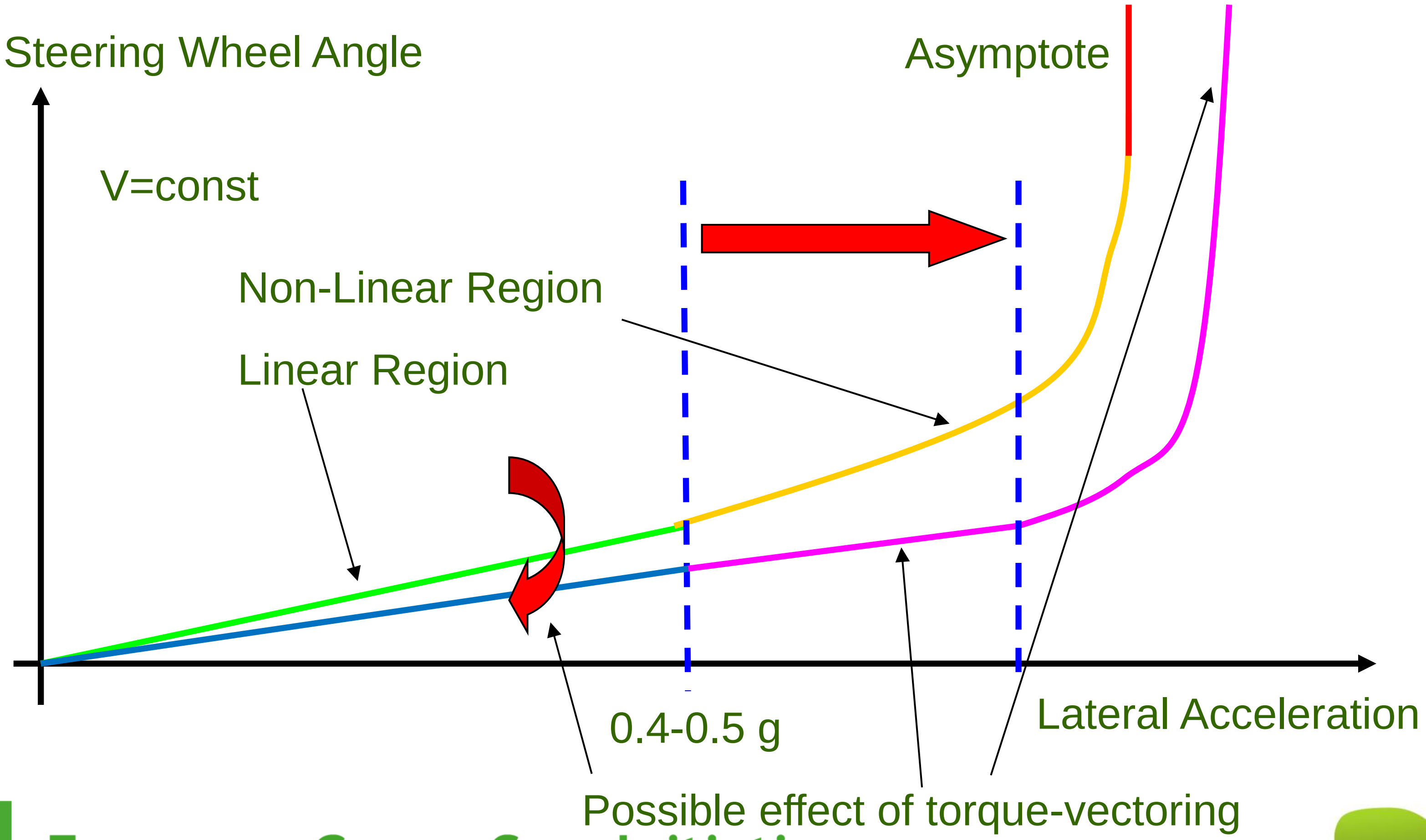
2. The objectives of the torque-vectoring controller

Objectives of the E-VECTOORC vehicle controller for multiple electric powertrains:

- To continuously achieve a defined understeer gradient target response in steady-state conditions
- To compensate the variation of vehicle response induced by braking/acceleration
- To reduce the variation of vehicle response during transient conditions
- Relatively simple control structure easy to implement on a real vehicle demonstrator

2. The objectives of the torque-vectoring controller

'Design' of the reference understeer characteristic through torque-vectoring control



Steering Wheel Angle

Asymptote

V=const

Non-Linear Region

Linear Region

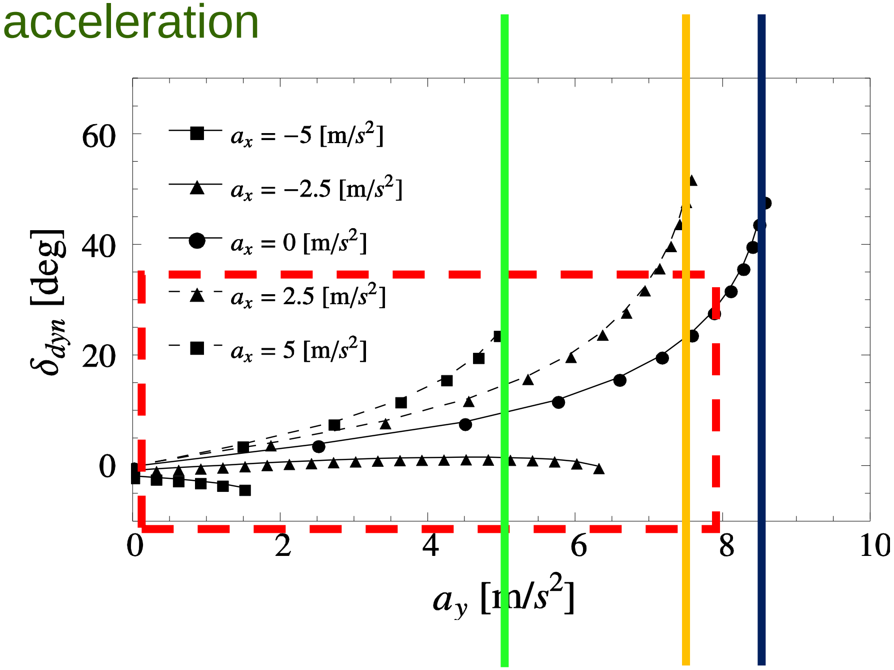
0.4-0.5 g

Lateral Acceleration

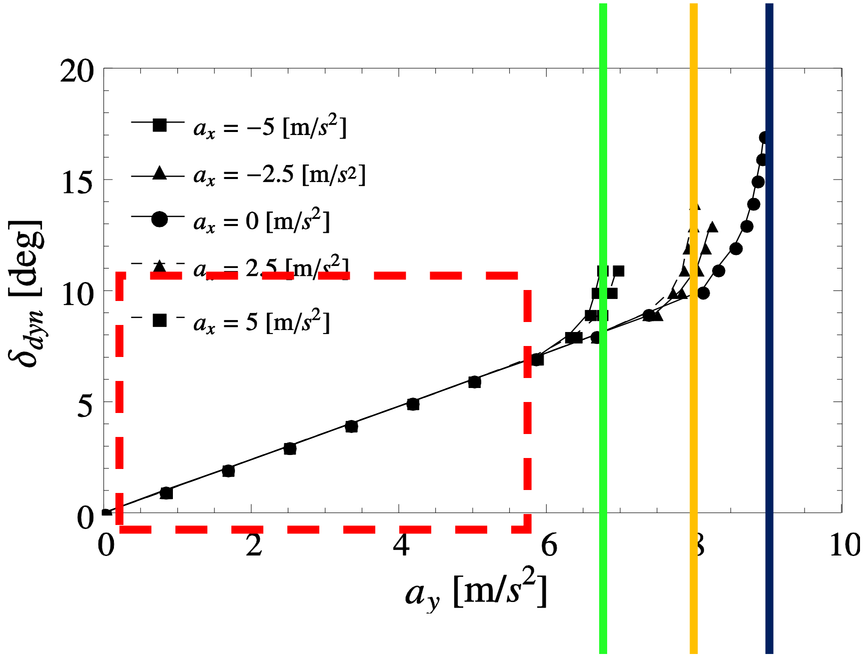
Possible effect of torque-vectoring

2. The objectives of the torque-vectoring controller

The understeer characteristic significantly varies as a function of longitudinal acceleration



Vehicle with constant torque distribution

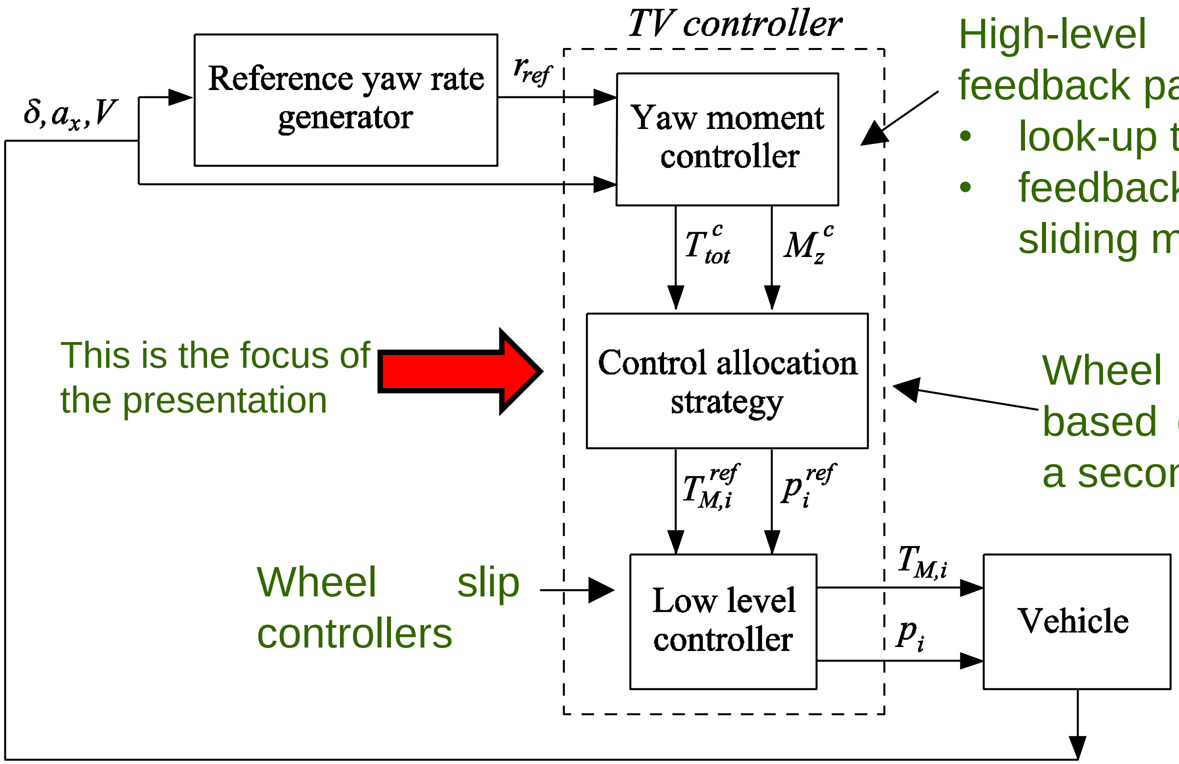


E-VECTOORC vehicle

This is a complete redesign of vehicle behaviour. Several driving modes are possible for the same vehicle. They can be selected by the driver

3. The E-VECTOORC control structure

The proposed E-VECTOORC yaw moment control scheme for fully electric vehicles presents a hierarchical structure



High-level controller (feedforward part and feedback part)

- look-up tables of $M_z^{FF}(\delta, TD, V)$
- feedback control structure (e.g. PID or sliding mode)

This is the focus of the presentation

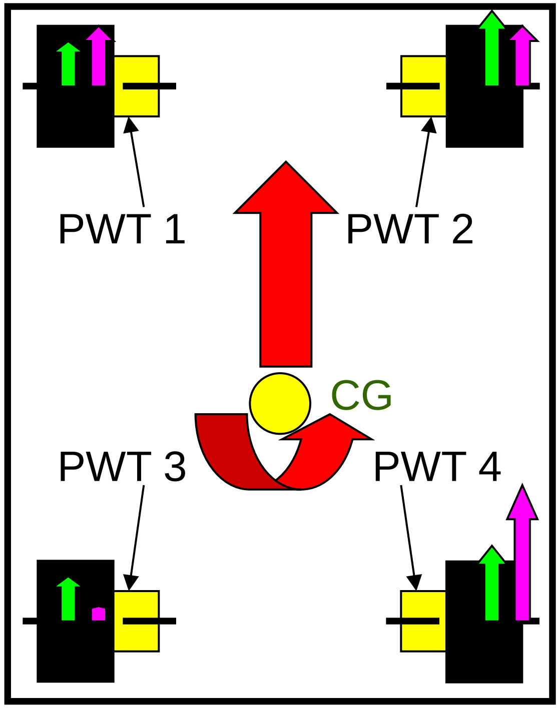
Wheel torque allocation algorithm (rule-based or on-line optimisation minimising a secondary cost function)

Wheel slip controllers

4. The comparison of the cost functions for wheel torque allocation

Aim: to compare different wheel torque distribution criteria (control allocation criteria) providing the same target understeer characteristic and overall wheel torque or longitudinal acceleration

Torque-vectoring control with 4 electric drivetrains



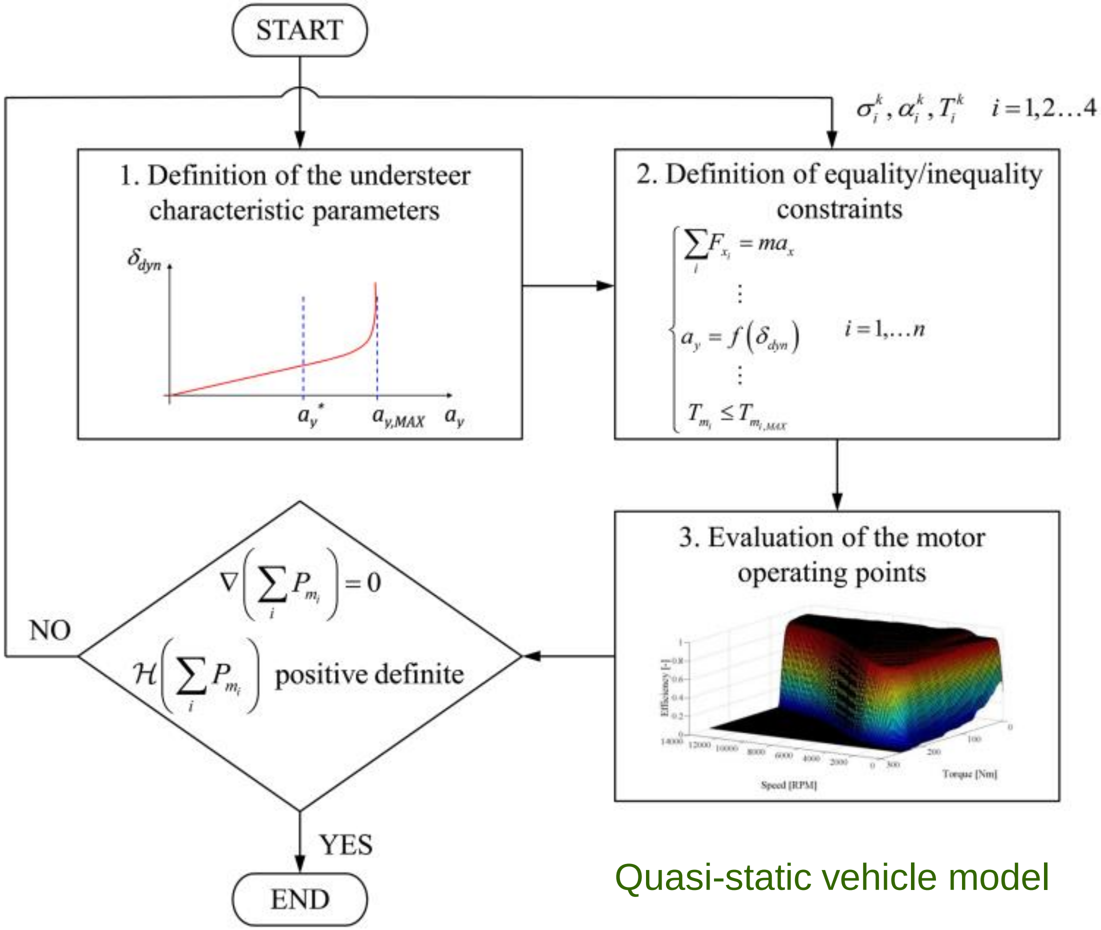
- Recent publications (e.g. Chen and Wang, 2012) develop control allocation algorithms based on the minimisation of motor input power, with particular reference to the motor efficiency maps (without consideration of the other power losses)
- Other publications (e.g. Naraghi, Roshanbin and Tavasoli, 2010) calculate the wheel torque distribution based on the force distribution among the four tires
- An objective comparison of different wheel torque allocation criteria is absent in the literature
- On-line control allocation algorithms are very complex and rely on significant numerical approximations related to the formulation of the specific cost function
- The best way of evaluating different wheel torque distribution criteria is through a specific offline procedure, providing the comparison without the influence of the implementation details of the real-time software

4. The comparison of the cost functions for wheel torque allocation

Optimisation procedure

- The comparison of different wheel torque distribution criteria providing the same vehicle yaw response is based on an optimization procedure applied to a quasi-static vehicle model

- This approach does not have the limitations and numerical issues deriving from the implementation of the controllers in the time domain (on-line wheel torque control allocation problem). This allows a fair comparison of the objective functions



START

$\sigma_i^k, \alpha_i^k, T_i^k \quad i = 1,2\ldots4$

1. Definition of the understeer characteristic parameters

2. Definition of equality/inequality constraints

$$\begin{cases} \sum_i F_{x_i} = ma_x \\ \vdots \\ a_y = f(\delta_{dyn}) \qquad i = 1,\ldots n \\ \vdots \\ T_{m_i} \le T_{m_i,MAX} \end{cases}$$

3. Evaluation of the motor operating points

$\nabla\left(\sum_i P_{m_i}\right) = 0$

$\mathcal{H}\left(\sum_i P_{m_i}\right)$ positive definite

NO

YES

END

Quasi-static vehicle model

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4. The comparison of the cost functions for wheel torque allocation

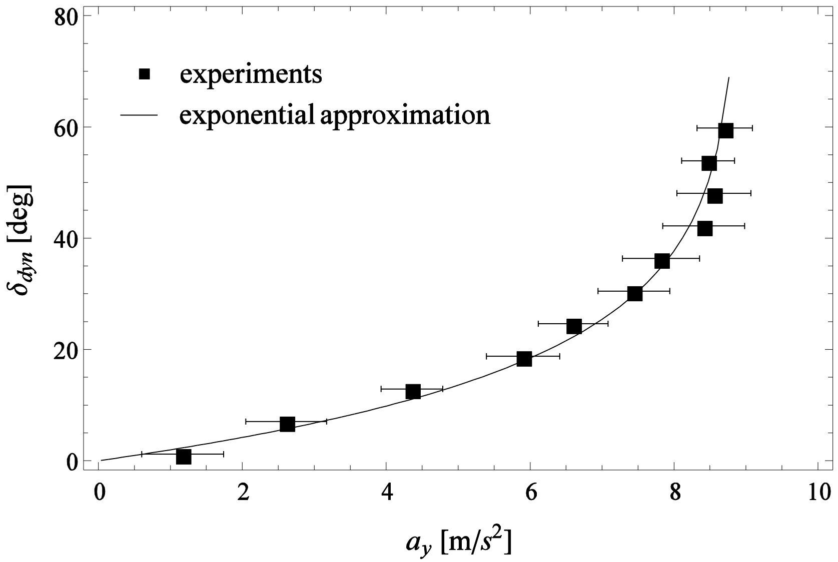
Step 1. Definition of the parameters of the reference understeer characteristics

Three parameters are adopted:

- the understeer gradient $k_u(a_x)$
- the linear region threshold $a_y^*(a_x)$
- the asymptotic value $a_{y_{max}}(a_x)$

The reference understeer characteristic can be represented through an exponential approximation:

$$\begin{cases} a_y = \dfrac{1}{k_u}\delta_{dyn} & if \quad \delta_{dyn} < a_y^* k_u \\ a_y = a_{y_{max}} + \left(a_y^* - a_{y_{max}}\right) e^{\frac{a_y^* k_u - \delta_{dyn}}{\left(a_{y_{max}} - a_y^*\right) k_u}} & if \quad \delta_{dyn} \geq a_y^* k_u \end{cases}$$

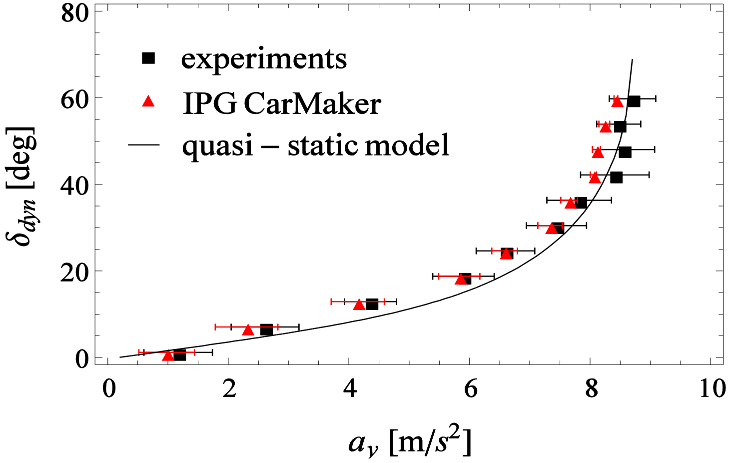


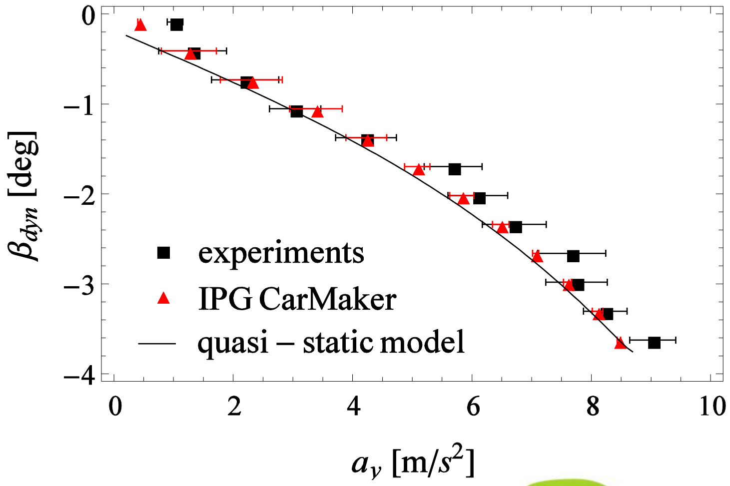
The fitting with the experimental results is very good

4. The comparison of the cost functions for wheel torque allocation

Step 3. is based on a quasi-static vehicle model (Abe, 1986)

- No numerical integration forward in time
- 8 degrees of freedom
- Pacejka ‘96 tyre model
- Easy derivation of the understeer characteristics at different longitudinal acceleration levels
- Easy derivation of the moment method plots and β-method plots
- Implemented to simulate any fully electric vehicle layout from 2 to 4 electric drivetrains (including torque-vectoring differentials)
- Experimentally validated during the E-VECTOORC project





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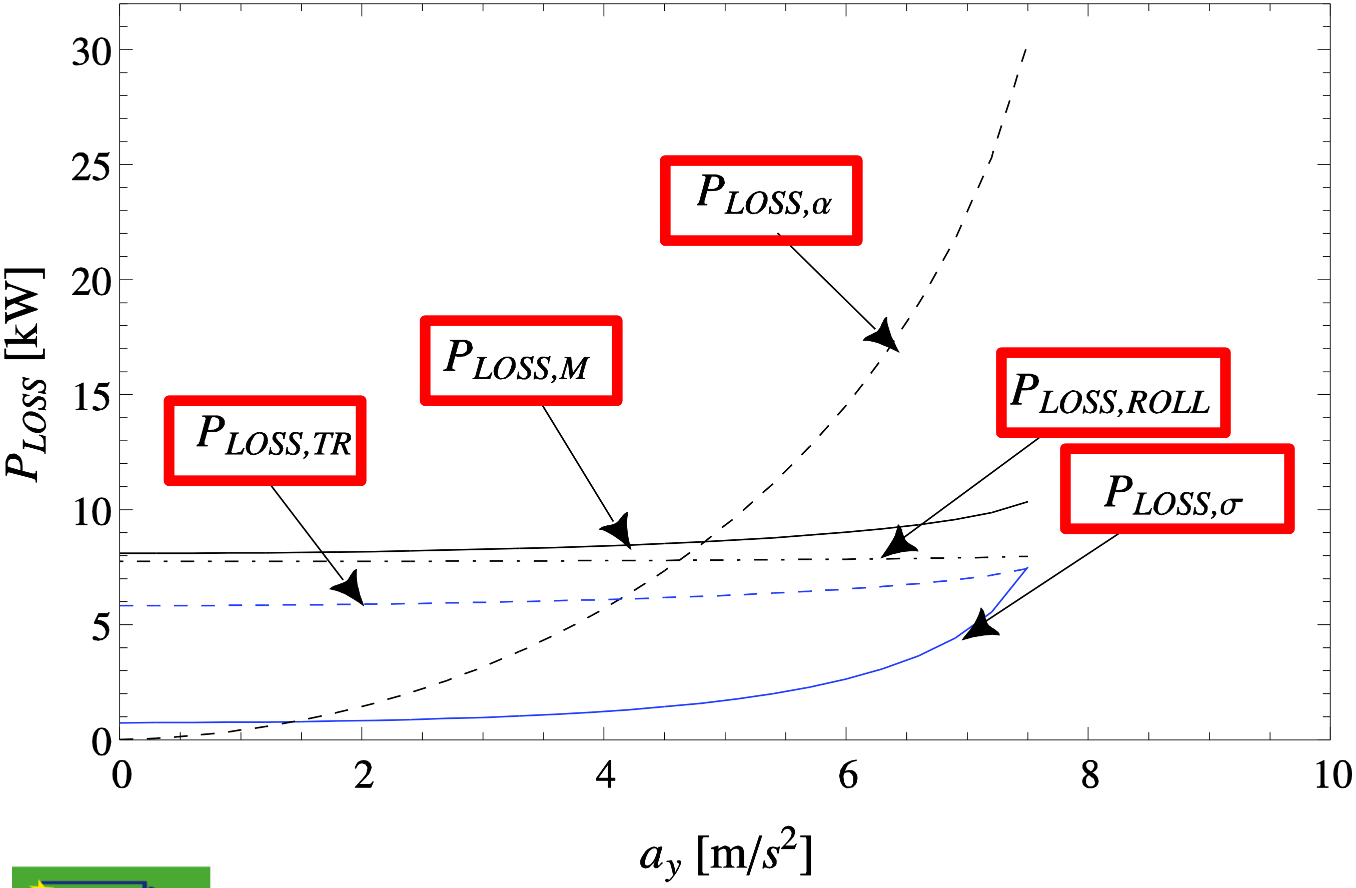
4. The comparison of the cost functions for wheel torque allocation

Detailed computation of the individual power loss contributions



- The slip power losses represent the most significant contribution at medium-high values of lateral acceleration
- The power losses can be a relevant criterion for deciding the torque split between the electric motor drives (control allocation)

V=90 km/h; a_x=2.5 m/s^2

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4. The comparison of the cost functions for wheel torque allocation

The following objective functions have been evaluated:

- Minimum input motor power

$$C_P = \min \sum_{i=1}^{n} \left(T_{m_i} \omega_{m_i} + P_{windage_i} + P_{LOSS,m_i} \right)$$

- Minimum slip standard deviation

$$C_{STD} = \min \sqrt{\sum_{i=1}^{n} \frac{{\sigma_i}^2}{4} - \left(\sum_{i=1}^{n} \frac{\sigma_{x_i}}{4} \right)^2}$$

- Minimum longitudinal slip power loss

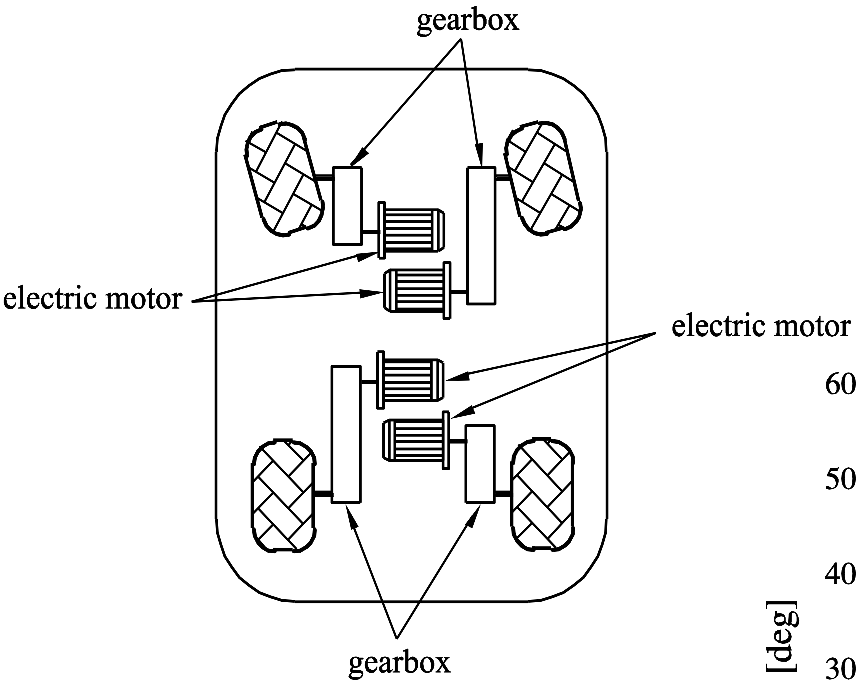
$$C_{SPL} = \min \sum_{i=1}^{n} F_{x_i} v_{s,x_i}$$

- Minimum tyre force coefficient

$$C_\mu = \min \sum_{i=1}^{n} \frac{\sqrt{{F_{x_i}}^2 + {F_{y_i}}^2}}{F_{z_i}}$$

5. Results

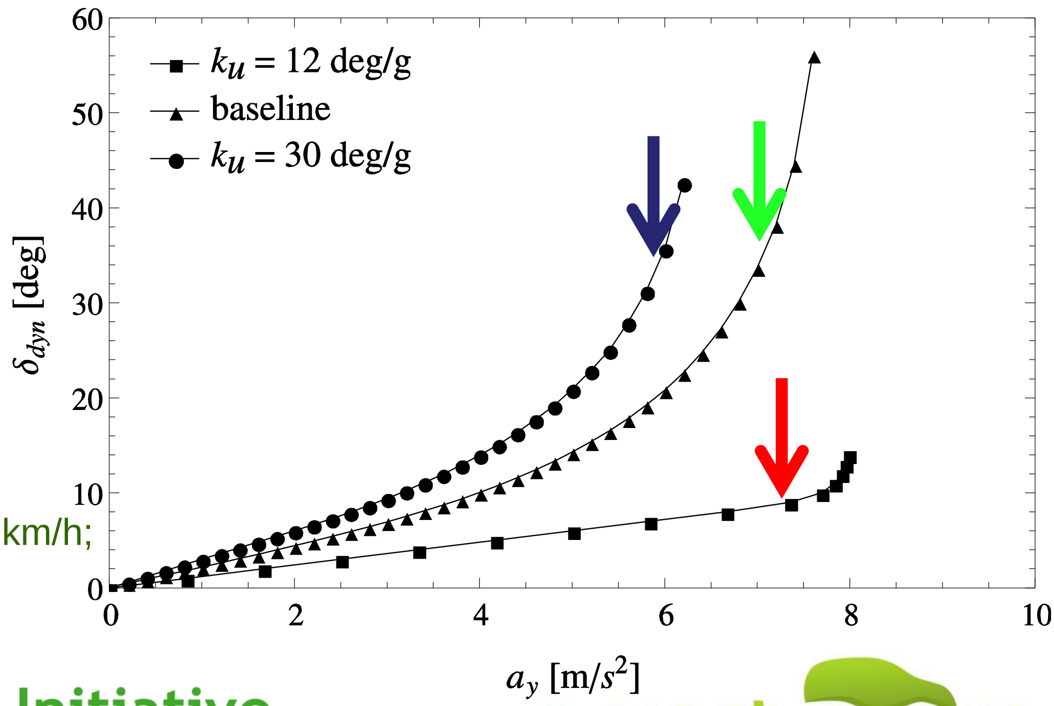
Case study vehicle



- Four on-board electric drivetrains

Main vehicle parameters

Overall vehicle mass	1950 kg
Front semi-wheelbase	1 m
Rear semi-wheelbase	1.6 m
Front and rear track width	1.625 m
Height of the vehicle centre of mass	0.66 m
Tyres	235/55 R19
Maximum electric motor power	≃100 kW



3 understeer characteristics evaluated at $V = 90$ km/h; $a_x = 2.5$ m/s^2

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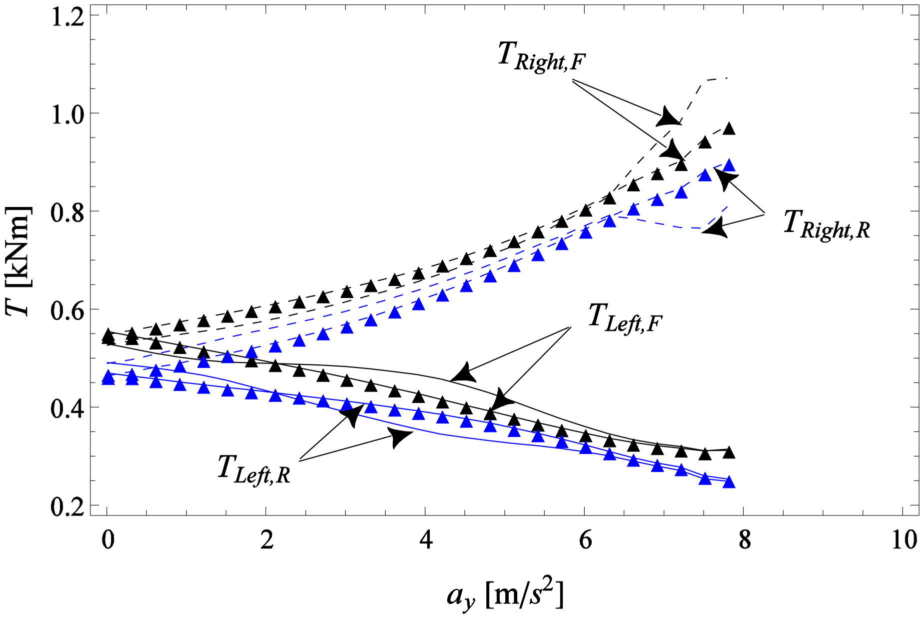
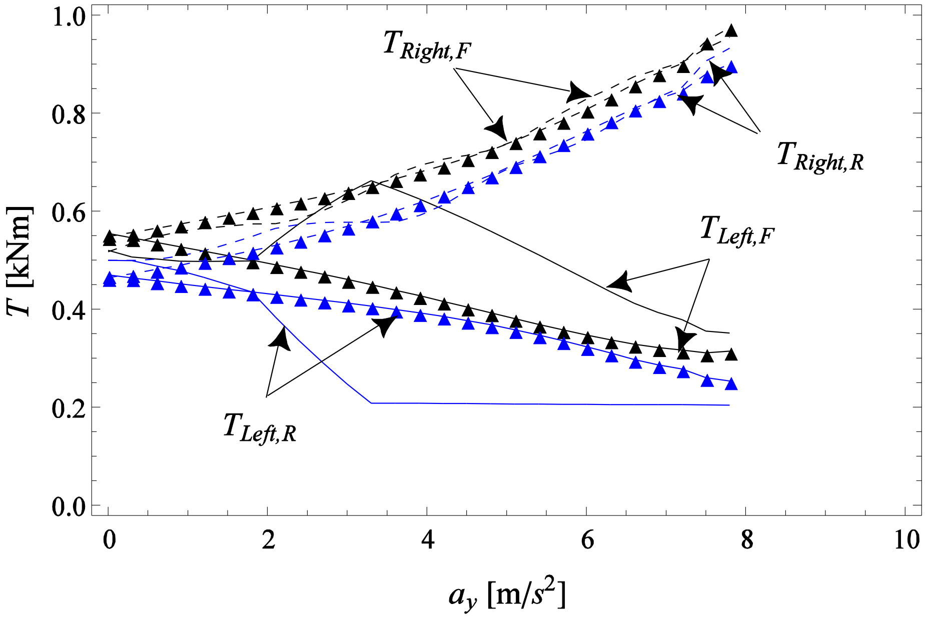
5. Results

Comparison of C_{SPL} and C_P – wheel torque profiles

Switched reluctance motor drive



Permanent magnet motor drive



C_{SPL}: line with markers; C_P: line without markers

- C_{SPL} allows a smoother trend of the wheel torques
- Potential drivability issues in the case of C_P

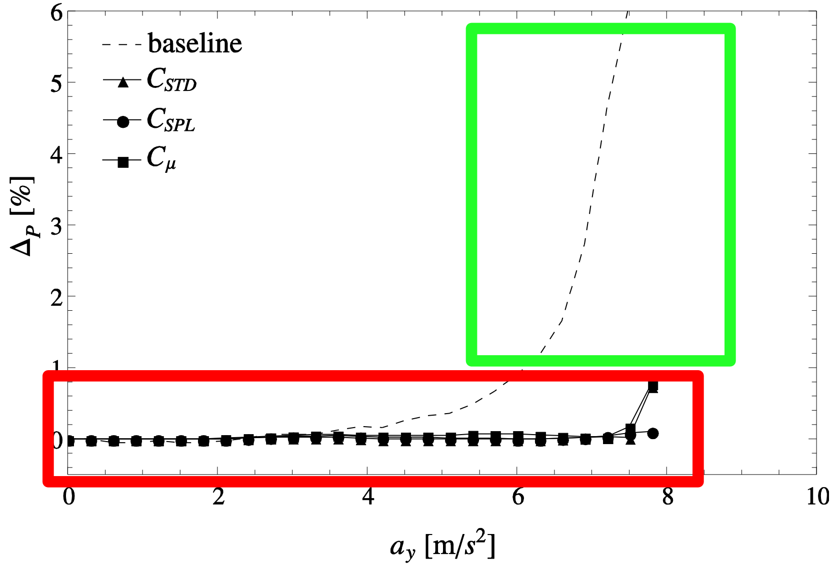
5. Results

Comparison of the cost functions – power input to the electric drivetrain

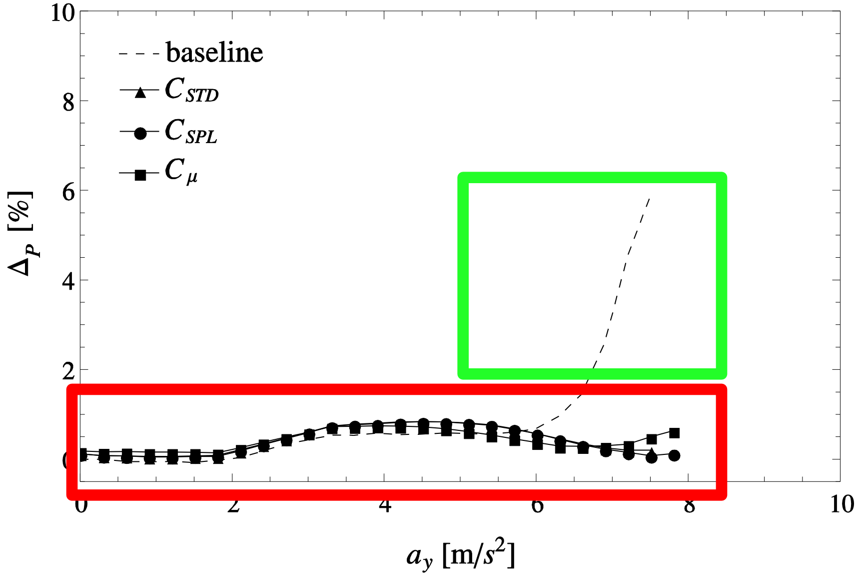
$$\Delta_P = \frac{P_{TV} - P_{TV,C_P}}{P_{TV,C_P}} \times 100$$

Percentage difference of the input motor power P_{TV} for a generic cost function and the input power for the cost function C_P (for the same understeer characteristic)

Switched reluctance motor drives



Permanent magnet motor drives



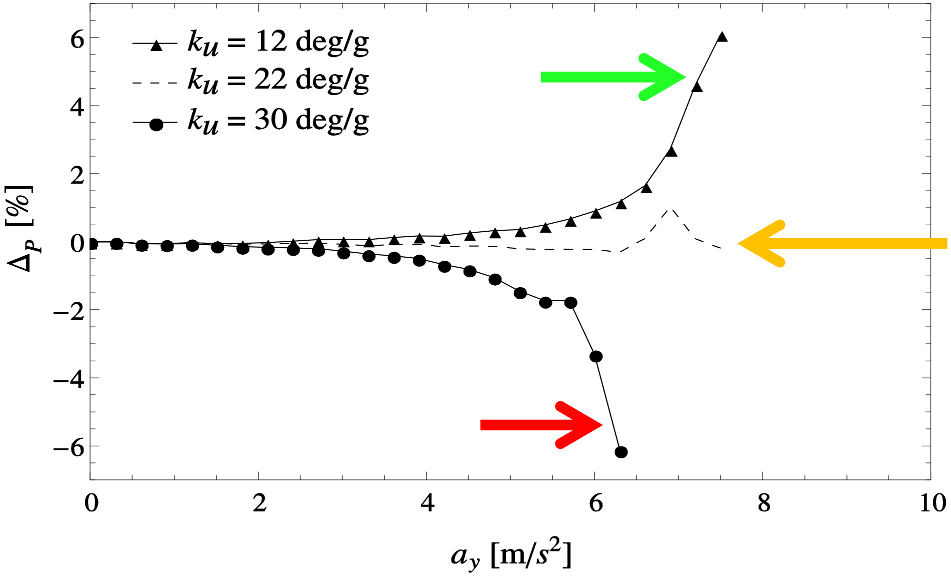
- C_{SPL} allows to achieve approximately the same input motor power as C_P
- The baseline vehicle is characterised by a significantly higher power input

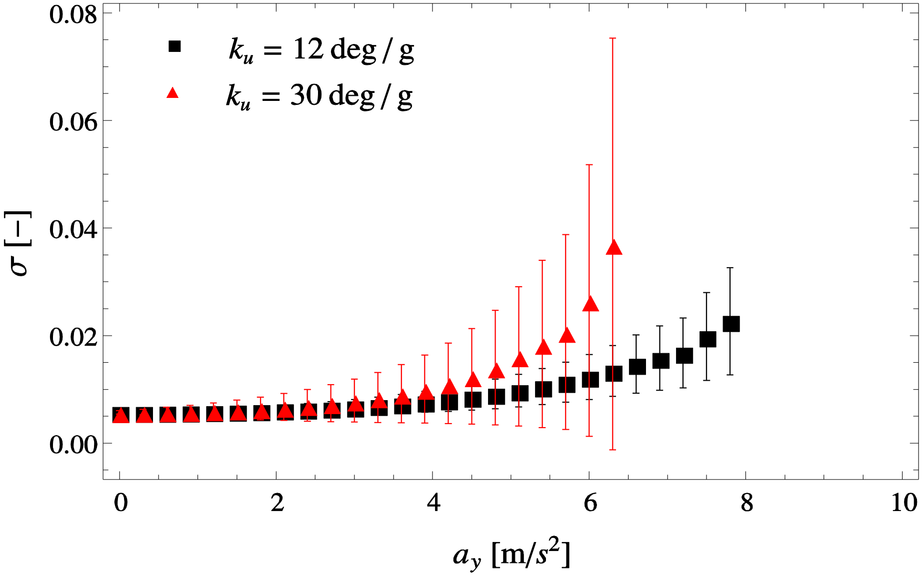
5. Results

Comparison of the target understeer characteristics – power input to the electric drivetrain

$$\Delta_P = \frac{P_{baseline} - P_{TV}}{P_{baseline}} \times 100$$

Percentage difference of the input motor power $P_{baseline}$ for a constant wheel torque distribution and the input power P_{TV} for the cost function C_P (calculated for an assigned reference understeer characteristic)





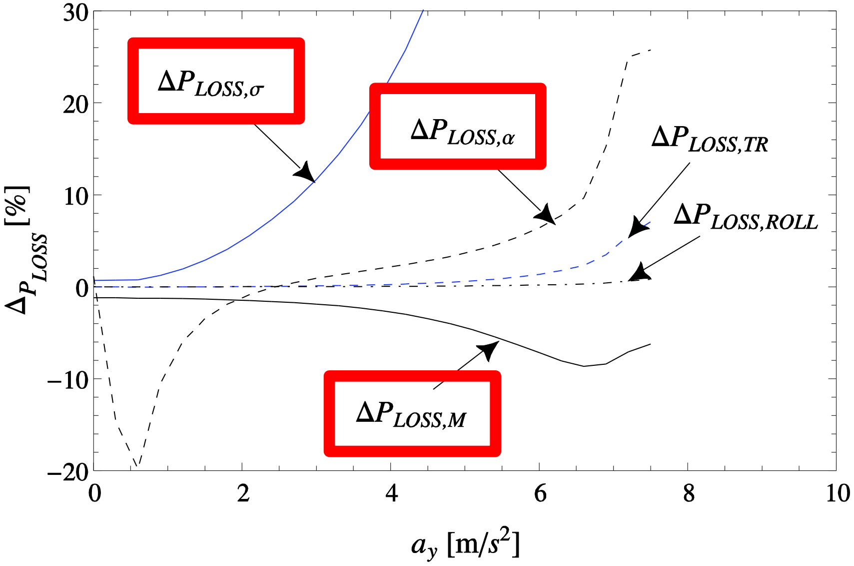
- The reduction of the understeer gradient in traction implies more uniform slip ratios and therefore lower motor power

5. Results

$$\Delta_{P_{LOSS}} = \frac{P_{LOSS_{baseline}} - P_{LOSS_{TV}}}{P_{LOSS_{baseline}}} \times 100$$

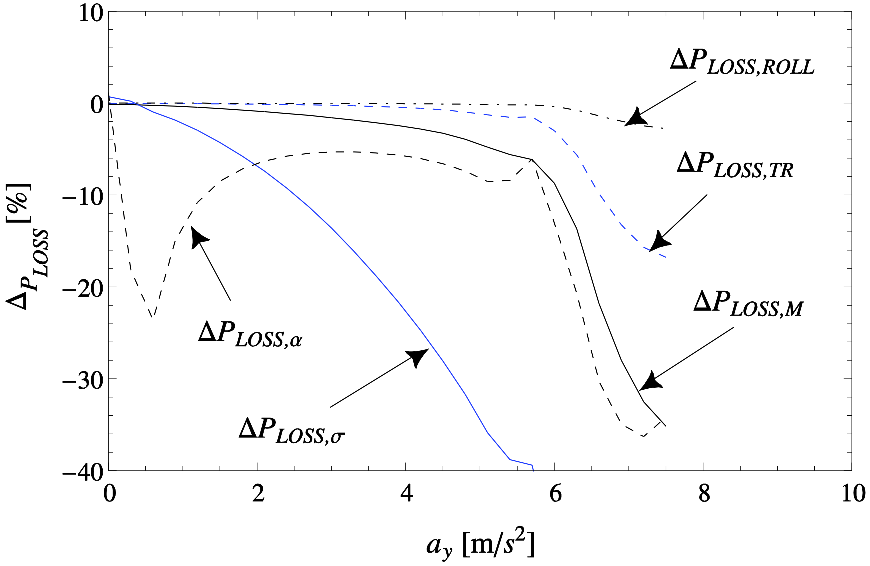
Percentage difference of the power loss $P_{LOSS,baseline}$ for a constant wheel torque distribution and the power loss $P_{LOSS,TV}$ for the cost function C_P (calculated for an assigned reference understeer characteristic)

K_U = 12 deg/g



- Higher motor power loss for the controlled vehicle
- Lower slip power losses for the controlled vehicle

K_U = 30 deg/g



- All the power loss contributions are higher for the controlled vehicle

6. Conclusions

- The steady-state and transient cornering characteristics of a fully electric vehicle can be ‘designed’ through the active control of the electric powertrains, rather than indirectly tuned via the common chassis parameters such as mass distribution and suspension elasto-kinematics
- Cost functions for wheel torque distribution based on the slip power losses bring a smoother variation of the drivetrain torques as functions of lateral acceleration, which is beneficial to drivability
- The results are dependent on the motor efficiency maps
- A significant correlation between the reference understeer characteristic and the input power to the electric powertrain has been observed
- The reduction of vehicle understeer in traction can bring an energy consumption benefit (up to 6% for the case study vehicle) due to the reduction of the tyre slip power losses
- Slip-based cost functions are highly recommended for wheel torque control allocation. They are also beneficial to vehicle safety as they reduce the potential occurrence of wheel spinning and locking

Any questions?

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The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n°284708

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