Driving dynamics and hybrid combined in the torque vectoring

Concepts of axle differentials with hybrid functionality and active torque distribution

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Overview
Driving dynamics and hybrid combined in the torque vectoring

Initiation
• Motivation
• Torque Vectoring and driving dynamics
• Simulation approach

2 Examples of “Hybridization with active torque distribution”
• Design
• Functionality

Evaluation results for longitudinal and lateral dynamics
• Layout and optimization of longitudinal dynamics
• Layout and optimization of lateral dynamics

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Motivation
Driving dynamics and hybrid combined in the torque vectoring

- **Active manipulation of lateral dynamics**
  - Torque Vectoring System

- **Active manipulation of longitudinal dynamics**
  - Traction advancement
  - Advancement of acceleration behavior

- **Hybrid function**
  - Energy recovery and boost function

- **Ease integration**
  - Moderate changes in driveline design and package
  - Preservation of engine and driveline configurations
  - Modularity and ability to retrofit
Positioning possibilities
Integration of electrical machines in the powertrain

At the Internal Combustion Engine

Quelle:vgl. VDI-Berichte Nr. 1943, 2006
Positioning possibilities
Integration of electrical machines in the powertrain

Quelle: vgl. VDI-Berichte Nr. 1943, 2006

Between Engine and transmission
(inline or parallel)
Positioning possibilities
Integration of electrical machines in the powertrain

Quelle: vgl. VDI-Berichte Nr. 1943, 2006
Positioning possibilities
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Positioning at transfer case

Quelle: vgl. VDI-Berichte Nr. 1943, 2006
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As Wheel Integration
(4x2 or 4x4 possible)

Quelle:vgl. VDI-Berichte Nr. 1943, 2006
Possible positions at the differential
Integration of electrical machines in the powertrain

1 electrical machine

Axle Torque Support

2 electrical machines

Wheel Individual Torque distribution possible

3 electrical machines
Axle differential with active torque distribution
Torque-Vectoring

Understeering driving behavior without active torque distribution

Active longitudinal and lateral torque distribution

Positive effect on
- Traction
- Critical cornering speed
- Self-steering response
- Handling and cornering characteristics
- Agility
- Yaw damping / yaw boosting
- Reducing brake intervention
Basic Optimization Targets
System Definition

- **Longitudinal Dynamics**
  - Optimal E-Machine Concept related to driving Cycle and performance targets
  - Optimal Battery Capacity related to driving Cycle
  - Optimal Hybrid Strategy related to driving Cycle

- **Lateral Dynamics and Driving safety**
  - Optimal E-Machine Concept and set-up for dynamic Torque Vectoring
  - Targets for mass distribution and self steer characteristics
  - Limitations to hybrid strategy under lateral dynamics
  - Necessary sub-controls for ASR/MSR and ESC Intervention

**Networked Simulation approach for Optimization and pre evaluation through virtual test runs**
Use of EXITE-ACE as co-simulation tool to connect IAV-powertrain model VeLoDyn and common handling simulation tool veDyna

**Powertrain model**
- detailed Powertrain model representing hybrid architecture and contains operational strategy

**Integration tool**

**Vehicle model**
- detailed vehicle chassis model
- detailed environmental description including a maneuver controller for longitudinal/lateral maneuver setup
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Summary
#1 Example, roughly equiv. to Lexus RX400h
Integration of electrical machines in the powertrain

Starter/Generator at ICE, 
Additional E- Machine at Rear Axle  
(Only virtual / SW 4WD clutch)

Also possible with Rear Axle Drive  
and E-machine at front axle

Quelle: vgl. VDI-Berichte Nr. 1943, 2006
Potential Hybrid strategy (w/ Rear Axle E-Machine)
Integration of electrical machines in the powertrain

- Battery charging during normal driving
- Basic Recuperation (engine drag torque superposition)
- Brake recuperation (system blending).
- AMT shift support (boost)
- Driving with E-machine only
- 4WD-strategy and rear axle boost
- Safety strategy for:
  - Driving with E-machine in "Active Short"
  - Erroneous Torque set-point / sign
  - Slip intervention (ASR/MSR)
  - ESC and ABS intervention (e.g. under coupled inertia)
Simulation settings
3d-Alpe d’Huez simulation

- Front and rear E-Machine scaled from longitudinal optimization
- Driver used form veDyna expect gear shifting
- All hybrid functions enabled
- SOC at start: 70 %
- 4WD torque split strategy:
  1. As much as possible with front axle, then add rear axle
  2. Permanent 4WD suport SOC dependent
- ASR on
- MSR on/off

→ Implementation of a ASR/MSR controller by IAV
Vehicle behaviour while regen. braking on Alpe d’Huez

3d-Alpe d’Huez simulation

160 seconds on the road

MSR/ESC off

Up-hill drive with max. of 800Nm recuperation torque at rear axle
Vehicle behavior while regen. braking on Alpe d’Huez

Example for over braking on rear axle while regenerative braking up-hill.
Integration of electric machines in the powertrain

#2 Rear Axle differential with active torque distribution

**Wheel-specific torque vectoring**
- Existing engine/transmission configurations (MT, AMT, DCT, CVT, AT) can be carried over
- Rear-axle module: supplier add-on
- Utilization of wheel-specific coefficient of friction

**Using a suitable storage system**
- Parallel hybrid
- Improved longitudinal dynamics
- Avoidance of traction interruption

Integration of two electric machines in the differential casing

Control

Energy storage

Optional for hybrid capability

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Design of active differential
Axle differential with active torque distribution

Flexibility and modularity
- Open differential
- Active differential
- ... with hybrid function
- Basis for electric axle
- Capability of integrating gear ratio
  → High degree of integration for electric machine without gear ratio
  → Existing mechanical structures and technologies carried over
  → Low additional moments of inertia, utilization of existing package
Hybrid functionalities
Axle differential with active torque distribution

- Hybrid functionalities
- Avoidance of traction interruption MT / AMT

4th gear, 85 km/h boosting

E-machine and generator torque:
2 x 350 Nm / 30 kW

24 kW
E-machine mode
350 Nm

24 kW
E-machine mode
350 Nm

600 Nm +350 Nm

1700 N +1000 N

1700 N +1000 N
Torque vectoring functionality
Axle differential with active torque distribution

Moving off with $\mu$-split

Mechanical torque transmission superimposed by electrical power flow when necessary

TV torque of 700 Nm for
- optimizing traction
- influencing transverse dynamics independently of drive torque
Traction potential in boosted mode
Tractive-power chart

Constant-speed driving without e-machines

![Graph showing traction and road load over velocity for different gears.](image)

- 1st gear
- 2nd gear
- 3rd gear
- 4th gear
- 5th gear
- 6th gear

Traction / running resistance [kN] vs. Velocity [km/h]
Traction potential in boosted mode
Tractive-power chart

Constant-speed driving boosted by e-machines (2 x 350 Nm)
Traction potential in boosted mode
Tractive-power chart

Constant-speed driving boosted by e-machines (2 x 350 Nm) and transmission

Velocity [km/h]
Traction / running resistance [kN]

Road load
Constant-speed driving only with e-machines (2 x 350 Nm)
Traction potential in boosted mode
Tractive-power chart

Constant-speed driving only with e-machines (2 x 350 Nm) and transmission
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Consumption potential in the NEDC
Simulations results of longitudinal dynamics

Power component from electric machines in NEDC

Full-load acceleration

<table>
<thead>
<tr>
<th></th>
<th>Boosted versus conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration from 0 – 100 km/h</td>
<td>-18.9 %</td>
</tr>
<tr>
<td>Acceleration from 80 – 120 km/h</td>
<td>-27.7 %</td>
</tr>
<tr>
<td>Acceleration from 80 – 160 km/h</td>
<td>-31.6 %</td>
</tr>
</tbody>
</table>

Consumption in NEDC

-4.1% Start-stop

Dependent on operating strategy

-9.5% to -15.5% Potential
Wheel-specific Torque-Vectoring
Simulations results of lateral dynamics ISO 4138

Steady-state skid-pad driving R = 100 m
(test to ISO 4138)

Self-steering response impact
→ predictable driving behavior also on upper lateral acceleration
→ increase the speed of cornering
→ possibility to recuperate transversal dynamics energy
→ possibility to realize a lane keeping system
Wheel-specific Torque-Vectoring
Simulations results of lateral dynamics ISO 7401

Step steering-angle change from 0 to 50° (300°/s at 80 km/h, test to ISO 7401)

Driving dynamics impact

→ low response time by fast actuator speed (~10 ms)
→ enhancement of steering response (yaw rate gain)
→ reduction of undesired yaw rate response (yaw rate amortization)
→ reduction of body motion
Wheel-specific Torque-Vectoring
Simulations results of lateral dynamics FMVSS 126

Sine with dwell for 6.5xA
(test to FMVSS 126)

Driving stability impact
→ impact of tracking stability
→ vehicle stabilization without braking
→ increase of driving dynamics by pre controlled intervention
Influence of additional torques for stabilizing potential
Based on: FMVSS 126 at max. steering angle amplification

Simulated Vehicle category: SUV, (not fully verified)
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Hybrid control with active torque distribution

Positive effect on longitudinal and lateral dynamics
- Assist cornering behavior and vehicle stabilization
- Offer traction optimization, boost function and shift support at MT and AMT

Parallel hybrid
- Electric machines provide the basis for hybridized powertrain

Benefits of electric machines direct at the differential
- Use of existing engine/transmission configurations
- Integrative, flexible and modular solution
- Very short control response time to provide the demanded driving dynamics intervention

Drawbacks
- Additional costs and weight related to standard TV
- Advanced control necessary
Thank you

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