A Novel Seamless 2-Speed Transmission System for Electric Vehicles: Principles and Simulation Results

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Presentation Outline

- Introduction
- Why a 2-speed Transmission for Electric Axles?
- The Novel Transmission Layout
- The Model and the Controller
- Results
- Conclusions
Introduction

Automotive Products

- High performance car transmissions
- 4WD car power transfer units and differentials
- Electric vehicles gearboxes and transaxles
Why a 2-Speed Transmission for Electric Axles?

Wheel Torque

Performance benefit of a 2-speed transmission (higher torque in 1st gear and higher speed in 2nd gear)

Constant torque region

Constant power region

Operating area with single-speed

Base speed

Vehicle Speed

SAE International
Why a 2-Speed Transmission for Electric Axles?

The optimisation of the 2\textsuperscript{nd} gear ratio permits to increase the overall efficiency of the electric powertrain.

Motor Downsizing
The performance benefit is achievable only in case of absence of torque gap during the gearshift.

The 2-speed transmission needs to be cost effective when compared to the single-speed transmission.
The Novel Transmission Layout

<table>
<thead>
<tr>
<th></th>
<th>Single Speed</th>
<th>Generation 1</th>
<th>Generation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Input Torque [Nm]</td>
<td>250 - 300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Input Speed [rpm]</td>
<td>8000 - 12000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>30</td>
<td>49</td>
<td>38</td>
</tr>
<tr>
<td>Dimensions L x W x H [mm]</td>
<td>330 x 260 x 480</td>
<td>370 x 380 x 490</td>
<td>370 x 230 x 470 (*)</td>
</tr>
<tr>
<td>1st gear ratio</td>
<td>8.3 : 1</td>
<td>11.3 : 1</td>
<td>10.1 : 1</td>
</tr>
<tr>
<td>2nd gear ratio</td>
<td>N.A.</td>
<td>5.5 : 1</td>
<td>4.5 : 1</td>
</tr>
<tr>
<td>Park lock (double engage)</td>
<td>N.A.</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Park lock (dedicated)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>OPTIONAL</td>
</tr>
</tbody>
</table>

(*) INSTALLATION ON VEHICLE: HORIZONTAL INSTEAD OF VERTICAL

Patent pending layout

The Novel Transmission Layout
The Novel Transmission Layout

UPSHIFT

DOWNSHIFT

Torque

Speed

Torque Phase
Inertia Phase

time

Torque Phase
Inertia Phase

Electric Motor Torque
Transmittable Friction Clutch Torque
Sprag Clutch Torque

Electric Motor Speed
1st Gear Speed
2nd Gear Speed
The Model and the Controller

- Dynamic Performance Model
  - Driver model
  - Half-shaft Dynamics
  - Electric Motor Rise Time
  - Efficiency Model
    - Efficiency Model
      - Speed
      - Torque
      - Temperature
  - Therm. model
  - Tyre Non-linear Dynamics (Longitudinal Force vs. Slip Ratio and Relaxation Length)

Torque Demand → Vehicle Speed

Input Speed → Efficiency Model
Input Torque → Temperature

Kinematics → SR\text{theoretical} → Rel. Length → SR\text{del} → Magic Formula

\( V_x \) Wheel Speed → \( F_x \)
The Model and the Controller

- Electric Powertrain Model

1st gear
- 1 Degree of Freedom

\[ \dot{\theta}_{\text{diff}} = \frac{T_m i_1 \eta_1 \eta_{\text{diff}} - T_{fc} i_2 \eta_2 \eta_{\text{diff}} - T_{fc} \eta_1 \eta_{\text{diff}} + T_h}{(J_{\text{diff}} + 0.5 J_{\text{LHS}} + 0.5 J_{\text{RHS}})} \]

Motor Torque Contribution
Friction Clutch Torque Contribution
Half-Shaft Torque Contribution
Equivalent Moment of Inertia

- Increased during ‘TORQUE PHASE’ reducing output torque
- Total half-shaft torque
- High due to high 1st gear ratio
The Model and the Controller

- **Inertia Phase** - 2 Degrees of Freedom (motor/transmission)

\[
\ddot{\theta}_{\text{diff}} = \frac{T_f c i_2 \eta_2 i_{\text{diff}} \eta_{\text{diff}} - T_h}{(J_{\text{diff}} + 0.5J_{\text{LHS}} + 0.5J_{\text{RHS}}) + J_{1b} i_2^2 \eta_2^2 i_{\text{diff}}^2 \eta_{\text{diff}} + J_2^2 i_{\text{diff}}^2 \eta_{\text{diff}}}
\]

\[
\dot{\theta}_m = \frac{T_m - T_f c}{\frac{J_{2b}}{i_1^2 \eta_1} + J_m + J_1}
\]

Low Equivalent Moment of Inertia
- Due to no contribution from the Electric Motor

**Golden Rule**: during the inertia phase of the gearshift, vehicle acceleration is controlled by the friction clutch torque, whilst electric motor dynamics are controlled by the motor torque

- **2nd Gear** engaged

\[
\ddot{\theta}_{\text{diff}} = \frac{T_m i_2 \eta_2 i_{\text{diff}} \eta_{\text{diff}} - T_h}{(J_{\text{diff}} + 0.5J_{\text{LHS}} + 0.5J_{\text{RHS}}) - (J_m + J_1 + J_{1b}) i_2^2 \eta_2^2 i_{\text{diff}}^2 \eta_{\text{diff}} + \frac{J_{2b} i_2^2 \eta_2^2 i_{\text{diff}}^2 \eta_{\text{diff}}}{i_1^2 \eta_1} + J_2^2 i_{\text{diff}}^2 \eta_{\text{diff}}}
\]

Lower moment of inertia than 1st gear due to \(i_2 < i_1\)
The Model and the Controller

Inertia Phase - Upshift

Electric Motor Torque Control (according to the Golden Rule)

\[ T_{m,\text{ref}} = (\Delta \text{DTD}) \]

[DTD = DRIVER TORQUE DEMAND]

\( \dot{\theta}_{\text{reference},m} = \dot{\theta}_{m,1\text{st~gear}} \cdot y \)

(motor ref speed)

\( \dot{\theta}_m \) (motor speed)

DTD

Feedback (PID)

Feedforward

(follow ref speed profile)
The friction clutch transmits the same amount of torque the electric motor would generate according to:

- **Driver Torque Demand** (unmodified)
- **actual motor speed**

**Control 1**

Inertia Phase - Upshift

(Diagram showing the relationship between torque and time during different phases.)
The Model and the Controller

Inertia Phase - Upshift

- **Control 2**

Friction Clutch Torque Controls (according to the Golden Rule)

The friction clutch transmits the same amount of torque the electric motor would generate according to:

- **Driver Torque Demand** (unmodified)
- **motor speed in 2nd gear**
The Model and the Controller

Torque Phase – Upshift

- **Control 3**

Motor Torque Demand

- Reduction of wheel torque during power transition from sprag clutch to friction clutch

- Increase of motor torque that compensate the reduction of wheel torque during power transition from sprag clutch to friction clutch

Common for Control 1 and 2

Time

First gear

Second gear

OBVIOUSLY UP TO MAX TORQUE
Results

Upshift in the constant torque region of the electric motor

- Complete absence of torque gap during the upshift
- Control 1 equivalent to Control 2

![Graph showing vehicle speed and motor torque](image-url)

![Graph showing jerk during upshift](image-url)
Results

Upshift in the constant power region of the electric motor

Control 2
Results

Upshift in the constant power region of the electric motor

Motor Torque vs. Motor Speed

- Control 1: torque gap during the inertia phase and low jerk
- Control 2: no torque gap during the inertia phase but high jerk (in any case always within a tolerable threshold i.e. < 25 m/s^3)
# Results – Sensitivity Analyses

- Control 1 vs Control 2 vs Control 3

<table>
<thead>
<tr>
<th>Torque Demand</th>
<th>40 – 100 km/h</th>
<th>70 – 100 km/h</th>
<th>Upshift time</th>
<th>Mean acceleration during upshift</th>
<th>Mean jerk during upshift</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>80%</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control 1</td>
<td>6.53 s</td>
<td>4.03 s</td>
<td>0.95 s</td>
<td>1.82 m/s²</td>
<td>2.24 m/s³</td>
</tr>
<tr>
<td>Control 2</td>
<td>6.33 s</td>
<td>3.84 s</td>
<td>0.70 s</td>
<td>2.25 m/s²</td>
<td>3.22 m/s³</td>
</tr>
<tr>
<td>Control 3</td>
<td>6.31 s</td>
<td>3.82 s</td>
<td>0.74 s</td>
<td>2.31 m/s²</td>
<td>2.15 m/s³</td>
</tr>
</tbody>
</table>

- Friction Clutch Actuator Rise Time
  (longitudinal acceleration test at 100% of driver torque demand)

<table>
<thead>
<tr>
<th></th>
<th>Actuator rise time: 100 ms</th>
<th>Actuator rise time: 200 ms</th>
<th>Actuator rise time: 300 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upshift time</td>
<td>0.83 s</td>
<td>1.18 s</td>
<td>1.53 s</td>
</tr>
<tr>
<td>0-100 km/h</td>
<td>8.65 s</td>
<td>8.75 s</td>
<td>8.84 s</td>
</tr>
</tbody>
</table>

- Motor Time Constant

<table>
<thead>
<tr>
<th></th>
<th>Motor time constant: 40 ms</th>
<th>Motor time constant: 80 ms</th>
<th>Motor time constant: 120 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 km/h</td>
<td>8.65 s</td>
<td>8.70 s</td>
<td>8.78 s</td>
</tr>
</tbody>
</table>
Results

Development Vehicles

Control 1
Control 2

2011 LCV event UK (September)
Conclusions

• The adoption of a 2-speed transmission can be an effective way to increase the performance and the efficiency of an electric axle

• A novel 2-speed transmission system design is proposed, based on the control of a friction clutch and a sprag clutch

• The implemented simulation models demonstrate the effectiveness of the transmission concept

• The novel transmission system permits the independent control of the electric motor dynamics and the vehicle acceleration dynamics during the gearshift

• The main parameters affecting the gearshift dynamics are: motor inertia friction clutch actuator dynamics (rise time) and motor dynamics

• The prototypes of the novel transmission system are under testing on a vehicle demonstrator and on the Hardware-In-the-Loop powertrain rig of the University of Surrey