

Design and Experimental Demonstration of a Seamless Automated Manual Transmission using an Eddy Current Torque Bypass Clutch for Electric and Hybrid Vehicles

Marc-Olivier Lacerte, Gabriel Pouliot, Jean-Sébastien Plante, and Philippe Micheau
Université de Sherbrooke

ABSTRACT

Electric Vehicles (EVs) with single-ratio gearbox provide high levels of smoothness, but using multi-speed gearbox can provide significant benefits in terms of vehicle acceleration, top speed, powertrain cost, mass, and energy consumption. In particular, Automated Manual Transmissions (AMTs) have characteristics of smooth shifts without torque interruption when coupled to a torque bypass clutch. However, conventional friction clutches are not best suited as torque bypass clutches because of their limited controllability and because large amount of heat must be dissipated to slow down the motor during gearshifts. This paper studies the feasibility of a seamless AMT architecture for EVs and Hybrid Electric Vehicles (HEVs) using an eddy current torque bypass clutch that is highly controllable, robust, low cost, and has no wearable parts. A system-level study using a backward-facing model is used to assess the advantages of multi-speed gearboxes for EVs in terms of energy consumption, powertrain cost, and mass. A full-scale clutch prototype is designed for a custom two-speed AMT of an 80 kW EV. Numerical simulations show that a two-speed gearbox can improve energy consumption by 7.2 % for a compact class EV such as the Nissan Leaf. Moreover, using two gear ratios allows a downsizing of the electric motor, which could reduce powertrain cost and mass by 23.1 % and 15.6 %, respectively. The clutch is characterized experimentally and its maximum torque agrees well with analytical results (within 6 %). The prototype performed a seamless shift on a test bench demonstrating the viability of using an eddy current clutch for torque bypass clutches in AMTs.

CITATION: Lacerte, M., Pouliot, G., Plante, J., and Micheau, P., "Design and Experimental Demonstration of a Seamless Automated Manual Transmission using an Eddy Current Torque Bypass Clutch for Electric and Hybrid Vehicles," *SAE Int. J. Alt. Power*, 5(1):2016, doi:10.4271/2015-01-9144.

INTRODUCTION

Motivation

Wide diffusion of Battery Electric Vehicles (BEVs) is currently limited by their lack of range and high purchase costs. The battery pack is the most expensive component for a BEV with a cost around 500 \$/kWh for dominant Li-ion chemistries [1]. At the module level, Li-ions batteries specific energies used in most EVs range from 80-120 Wh/kg [2], depending on cell chemistry and packaging layout. In comparison, gasoline has a specific energy of 12,000Wh/kg [3, 4]. Even if the tank-to-wheel optimum efficiency of a BEV is about 80-85% compared to 10-30% for spark ignition engine vehicles [3, 5-6], the vehicle range for the same mass of on-board energy will be significantly lower for BEVs. The increase of the on-board energy doesn't increase the vehicle range proportionally, because of higher vehicle consumption caused by rolling resistance and inertial forces. Powertrain efficiency must therefore be maximized in order to reduce battery size and purchase cost of BEVs and HEVs.

Background and Literature

Most conventional EV traction systems employ a Permanent Magnet Synchronous Motor (PMSM), coupled with a single-speed gearbox in a central drive configuration. Despite high starting torque and wide constant power operation region of PMSMs, the use of a single-speed gearbox requires a motor with high torque to achieve acceptable levels of acceleration and gradeability. As the EV market grows, consumers will have greater expectations in terms of launch performances and vehicle maximum speed. First generation EVs use single-speed gearboxes as it represents less development effort and there is no traction force interruption. This trade-off leads to the need for larger and thus more expensive motors, due to high costs of rare-earth magnets, electrical steel for stator and rotor laminations and copper windings. Moreover, the direct mechanical connection between the motor and the wheels prevent the motor from operating in its optimum efficiency region. The use of a single-speed gearbox thus results in a sub-optimal use of the battery energy [7].

Series HEVs represent the simplest architecture among hybrid powertrain architectures, although they require two electric motors and an internal combustion engine of large size for long-distance sustained, high-speed driving. This arrangement is not the most efficient in charge-sustaining mode because of the driving power

suffers conversion losses through the electrical path. The use of a two-speed transmission in series HEVs has proven to reduce the size of the traction motor whilst maximizing its efficiency, especially at higher driving speeds [8, 9, 10]. In contrast, parallel HEVs require only one electric motor and offer a highly-efficient mechanical path to transmit both power sources to driven wheels. However, engine speed is constrained by a finite number of gear ratios that can potentially lead to an inefficient engine operation (e.g. urban driving). The Electronic-Continuously Variable Transmission (e-CVT), like the Hybrid Synergy Drive from Toyota, presents advantages of both parallel and series arrangements. However, this power-split system is designed with a mindset of blended strategy, for the purpose of a more efficient use of the liquid fuel [8]. The limited on-board electric storage and the lack of performance in all-electric mode therefore require engine operation (fuel consumption) under everyday load conditions [11]. Power-split architectures are complex and expensive, as they require two electric machines and at least one epicyclic gear train to continuously vary the engine speed ratio. Another major drawback of power-split HEVs is the limitation of the total tractive force, by the weakest side of the split. Hence, the power-split powertrain layout is not optimal to simultaneously deliver maximal on-board mechanical power and provide good vehicle performances.

Theoretical simulations and field tests show improvements in the energy consumption ranging from 4 to 15% for EVs equipped with a two-speed gearbox, as compared to single-speed gearbox EVs [7, 10, 12, 13, 14, 15, 16, 17, 18, 19]. Variations in results depend mostly on the vehicle, motor and inverter specifications, drive cycle, regenerative braking constraints and shift schedule. Fundamentally, the relevance of multi-speed transmissions for EVs is based on the criteria of low cost, high degree of reliability and mechanical efficiency, as well as compliance with consumer's needs. The observed general trend toward driving comfort and shift quality leads the industry to upgrade from interrupted traction force transmissions to seamless transmissions [20, 21]. For efficiency, cost and complexity reasons, Automatic Transmissions (ATs) and Continuously Variable Transmissions (CVTs) are not ideal as multi-speed transmissions for EVs [21, 22]. Current ATs and belt type CVTs achieve maximum efficiencies of 86% and 85%, respectively, Manual Transmissions (MTs) have shown efficiencies of 96% [23].

AMTs are a potential candidate for EVs as they are easy to manufacture, robust and low cost. The slight reduction in mechanical efficiency compared to a single-speed transmission (~97%), due to additional churning and squeezing losses attributable to splash lubrication, is usually marginal compared to the benefit in the overall powertrain efficiency [15]. However, in a passenger car application using a two-speed transmission, a 100kW electric motor that upshifts at 10,000 Revolutions Per Minute (RPM) requires about half a second to synchronize its speed for the next gear engagement [24]. Recharging power limitations of the battery pack can easily double the duration of the torque interruption, which is not acceptable for EVs from a comfort perspective. Powershift transmissions capable of changing gears without torque interruption have been proposed and are shown schematically in Figure 1.

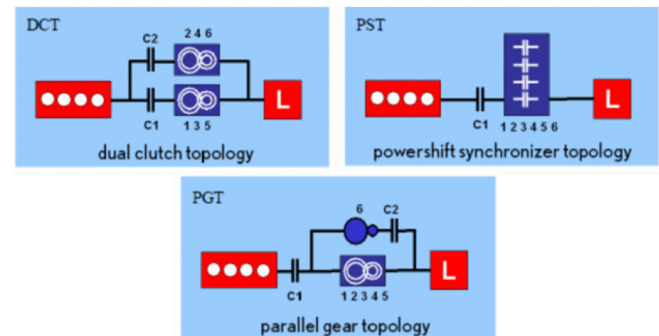


Figure 1. Schematic representation of powershift transmissions [25]

Dual wet Clutch Transmissions (DCTs) use hydraulic actuators and multi-plate wet clutches for better torque controllability and thermal dissipation, at the expense of efficiency due to drag and pump losses. More efficient DCTs use dry clutches and electromechanical actuators, but the high production cost and complexity still remains a challenge for their use in EVs [22, 25]. Issues regarding the primary side high moment of inertia, lining wear and thermal capacity of dry clutches can also be problematic for EVs, because of higher motor rotational speeds [25, 26]. Powershift Synchronizer Transmissions (PSTs) are defined as an AMT with oversized cone synchronizers, which lead to bulky and expensive components. The torque fill-in during gear shifts still remains partial, due to torque and thermal limitations of the synchronizers [25]. Cone wear, degradation in shift quality over time and challenge in torque control [27] make PSTs unsuitable as multi-speed transmissions for EVs. Parallel Gear Transmissions (PGTs) solve the ride comfort problem of AMTs by adding a friction clutch, enabling parallel torque transfer through the highest gear [25, 28]. During gearshifts, the clutch controls the amount of torque to the wheels and thereby helps to slow down the motor before the next gear engagement. Hitachi Group achieved torque fill-in by replacing the fifth gear of a traditional AMT by a multi-plate wet clutch [29]. Drag losses in the normally-open wet clutch are a big concern that must be addressed for EVs. Another issue for PGTs having a big ratio spread is the limited torque fill-in capability, especially during shifts from 1st to 2nd gear [25]. In conclusion, there are no multi-speed transmissions on the market that fully meet the requirements of EVs.

Approach, Results and Conclusion

This paper studies the feasibility of an AMT transmission architecture capable of torque fill-in that meets the high efficiency, robustness, low cost, and shift quality requirements of BEVs and HEVs. The proposed “Eddy-CT” transmission uses an eddy current torque bypass clutch that is highly controllable, uses readily available electric power, has no wearable parts, is reliable, and cost effective.

Analytical simulations of the impact of number of gear ratios on energy savings show that only two gears ratios can bring energy savings up by 7.2% for passenger EV such as the Nissan Leaf. The “Eddy-CT” transmission functioning is then explained for both BEV and HEV configurations. The detailed design of a transmission prototype for an all-electric 2001 Volkswagen Golf GTI is presented.

Finally, experimental results on a reduced power test bench suggest the “Eddy-CT” transmission could be a viable concept for multi-speed powershift transmissions for EVs and HEVs.

IMPACT OF A MULTI-SPEED TRANSMISSION FOR EVS

Vehicle Parameters

The vehicle used for energetic calculations is the Nissan Leaf (see Table 1), which is an all-electric compact vehicle equipped with a single-speed gearbox. Motor and inverter efficiency maps are based on the traction system MΦTIVE A¹ from TM4 Systèmes Électrodynamiques.

Table 1. Vehicle parameters

	Specification	Value	Unit
T_{max}	Motor max torque	280	Nm
P_{max}	Motor max power	80	kW
i	Gearbox ratio	7.92	-
η	Gearbox efficiency	97	%
v_{max}	Vehicle maximum speed	150	km/h
-	Acceleration time 0-100km/h	10,2	s
$LxWxH$	Vehicle dimensions	4.45x1.77x1.55	m
w	Wheelbase	2.7	m
m	Curb weight with 2 passengers	1675	kg
FR / RR	Weight distribution	59/41	%
A	Frontal area ¹	2.19	m ²
C_d	Aerodynamic drag coefficient	0,28	-
h	Center of gravity height	0.53	m
-	Tire type	Radial SR, TR ²	-
r	Tire radius	0.316	m
μ_r	Coefficient of static friction	0.85	-

¹: Calculation based on standard SAE J1263

²: Refer to [30] for the coefficient of rolling resistance f

A backward-facing model is used, as it is best-suited to assess energy consumption of different powertrains on standard drive cycles. At each time step, the model calculates the road loads, including aerodynamic drag, acceleration and rolling resistances. The model also accounts for kinetic energy recuperation during braking, with a limit of 50 % of available power sent to the batteries, to account for limitations defined by non-modeled components (e.g. battery pack C-rate and energy efficiency in recharge). The motor and inverter cooling is considered to be sufficient to provide the tractive power required by drive cycles. Gear ratios and motor maximum torque are chosen to keep at least the same power envelope as the original single-speed configuration. This strategy ensures that the acceleration time, gradeability criteria and top speed are respected. Combinations of gear ratios causing a power drop after a gearshift have also been eliminated, for shift quality reasons. The acceleration time calculated by the model shown in Figure 2 is 10.5s, which represents a 3% difference with the manufacturer data and is thus considered realistic.

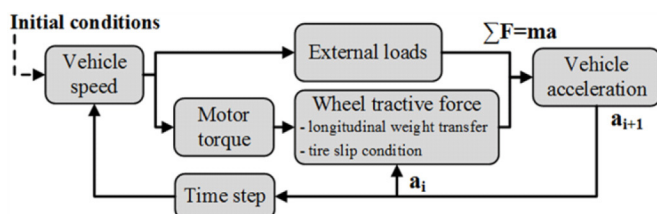


Figure 2. Model for gear ratio and motor torque calculations

1. <http://www.tm4.com/products/high-speed-electric-powertrain/motive-a/>, last consulted on 20th August 2014.

Standard drive cycles defined by the EPA are chosen to include urban (FTP75) and highway zones (SC03), as well as different levels of driving aggressiveness (US06). A cruising speed at 100 km/h is also considered in the energy consumption calculations.

Components Weight

The size and the mass m of an electric motor are directly related to its maximum torque T , as shown by the following relationship [31].

$$\frac{m_2}{m_1} = \left(\frac{T_2}{T_1}\right)^{0.75} \quad (1)$$

This relation has been confirmed by a benchmark of several PMSMs of different sizes, from several motor manufacturers. The benchmark confirms a relationship between the mass and maximum torque produced by a PMSM, and a proportionality factor of $\sim 7\text{Nm/kg}$ represents the market trend. The Nissan Leaf motor mass (single-speed configuration) has been estimated to 40kg with this trend. Results between equation (1) and the proportionality factor have a difference of roughly 20%, which is acceptable for this comparative study. For the assessment of transmission masses, the following equation is used [32].

$$m_g = 0.199 \left((i_{G,max} T_{motor})^{0.669} z^{0.334} \right) R_{corr} \quad (2)$$

Where $i_{G,max}$ is the highest first stage gear ratio, T_{motor} is the motor maximum torque and z is the number of gears. Equation (2) is a trend of mass m_g for coaxial two-stage passenger and commercial vehicle gearboxes (typically five-speeds). For small numbers of gear ratios, it is more accurate to correlate equation (2) with a one-speed gearbox. Using the BorgWarner eGearDrive (28kg), a correlation factor R_{corr} of 1.5 has been found.

Components Cost

First, a calculation of raw material cost has been completed using estimated motor masses [33]. To account for manufacturing, assembly, engineering development and overhead costs, a cost model has been found [34] to evaluate the cost of an electric traction system ($21 \$/\text{kW} + 425\$$). Comparison of these results leads to the conclusion that raw material represents about 30% of the production cost for PMSM. The cost model was not directly used for the motor cost assessment because the motor torque is not defined as an input parameter. To assess the transmission production costs, the following trend is used [32].

$$RSP = 0.0183 (i_{G,max} T_{motor})^{0.512} z^{0.256} \quad (3)$$

The relative selling price (RSP) is based on manually shifted passenger car transmissions. A RSP of 1 corresponds to a 6-speed transmission with an input torque $T_{motor} = 350\text{ Nm}$ and a maximum transmission ratio (1st gear) of $i_{G,max} = 5.5$. The production cost of this