

Multi-Speed Transmissions for Electric Drives

David Gagliardi¹, Carlo Cavallino²

¹*Oerlikon Graziano, Gmünder Straße 65, 73614, Schorndorf (Germany), david.gagliardi@oerlikon.com*

²*Oerlikon Graziano, Corso IV Novembre 53, 10098 Rivoli (Italy), carlo.cavallino@oerlikon.com*

Summary

The original assumption for electric vehicles and electric drivelines was to use a single-speed transmission, relying on the torque spread of the electric motor to provide adequate performance under all operating conditions. Though simple to execute, this arrangement cannot achieve the best vehicle efficiency because, for much of the time, the traction motor is operating at loads and speeds that do not yield optimum efficiency. This paper will show how an increase in transmission technology can reduce energy consumption and improve performance, and describe two multi-speed concepts which can even maintain or indeed reduce the overall electric powertrain cost and weight.

Keywords: BEV, PHEV, EV, electric drive, transmission

1 Introduction

The upcoming legislation limits for pollutants emissions are driving the OEMs to the electrification of powertrain. As part of this trend, a large number of new Battery Electric Vehicles (BEVs) is expected to be introduced into the market in the next years. Even if higher volumes will help to achieve economies of scale, the overall electric powertrain cost, including the energy storage system, will remain one of the key factors for the market success of such type of vehicles. In other words, particular care has to be dedicated to the right technology down-selection and system dimensioning. In particular, the improvement of powertrain efficiency helps to save battery size, therefore also weight and cost. On the other hands, similar or even better performances than comparable conventional vehicles have to be guaranteed in order to be attractive for the customers.

The current state of the art for electric vehicles has favoured the use of a ‘reducer’ – a simple single-speed reduction ratio between the electric machine and the differential over a multi-speed transmission. Whilst the initial promise of electric motors meant that selecting a single-speed transmission was sufficient, as electric powertrains develop, that choice is now not so clear. In the push to maximise system efficiency, improve pull-away performance, provide better gradeability, increase top-speed, downsize the motor and increase vehicle range, it is becoming clear a multi-speed transmission has a part to play in achieving all these aims across all vehicle classes, and at a fair on-cost in comparison to a single-speed device.

If a multi-speed gearbox is chosen, it is imperative that it is power-shifting – that is to say there is never a point in time where there is an interruption in torque to the driveline. In effect, the driver must be made unaware that the gearbox has made a change in ratio.

Oerlikon Graziano is keeping developing and improving two types of power-shifting multi-speed transmissions for electric drives, which will be presented in the next paragraphs.

2 Multi-speed transmissions for Electric Drives: 2SED and 4SED

The 2SED (2-Speed Electric Drive) is a power-shifting transmission that is now in its 3rd generation of design, which represents an evolution of the known gearbox with a novel electromechanical actuation system. Key element of this transmission is the low-complexity with respect to other power-shifting electric vehicle gearboxes. The latest refinements have been possible through the strategy of using demonstrator vehicles to prove a concept before being able to take it to the next stage of development.

The 4SED (4-Speed Electric Drive) represents an elegant solution for multi-speed transmission resulting even much simpler than a traditional manual gearbox; two electric are motors connected directly to two independent input shafts, omitting the need for any clutches. The four gears (2 per electric motor) are each selected by a dog engagement device utilising a single barrel cam to move the two required selector forks. Due to the architecture of this transmission, seven different states are possible in driving conditions, increasing the possibility of the electric motors operating in a high efficiency area for a given wheel torque/vehicle speed combination.

2.1 2SED

Despite the wide operational speed range of electric traction motors (currently achieving 16.000-18.000 or even higher rpm), a two-speed gearbox may be employed in order to increase the wheel torque at low vehicle velocity and, therefore, increase the maximum road gradient that the vehicle can ascend when transporting heavy payloads, for example, whilst also facilitating a reasonable top speed. Moreover, since in some cases the efficiency of the electric motor and inverter may vary significantly as a function of the operating torque and speed, the adoption of a two-speed gearbox can also facilitate significant benefits in terms of the energy consumption by optimizing the distribution of the operating points of the electric motor/inverter over a given driving schedule; the selection of the gear ratio being as important as in the case of a conventional vehicle driven by an internal combustion engine.

The 2SED is a two-speed gearbox which combines the mechanical simplicity of a layshaft type transmission, with the high quality of a clutch-to-clutch gearshift. Its primary components are a one-way sprag clutch located on the secondary shaft and a friction clutch on the primary shaft together with an open differential, as displayed in Figure 1. The input torque is transmitted by the sprag clutch while in first gear, and by the friction clutch while in second gear. The system can work either as a fully automated transmission or as an automated manual transmission through a seamless shift system.

The friction clutch is applied to transfer torque from the sprag clutch during an upshift and is released to allow the sprag clutch to engage to accomplish a downshift. The multi-disc friction clutch is electromechanically controlled using a brushless motor-driven actuator, as described separately in this paper. In order to allow regenerative energy recovery while decelerating in first gear, the engagement of a locking ring, electromechanically actuated, prevents the one-way sprag clutch from overrunning when the direction of torque through the transmission is reversed. Once the vehicle has come to rest, the gearshift mechanism can also be used as a park lock by simultaneously engaging the mentioned locking ring and closing the friction clutch, thus eliminating the need for a separate park lock mechanism and actuator.

The mechanical layout of the two-speed transmission results in a compact design, with the overall distance between the primary and differential shaft being about 200mm for a premium passenger car. Furthermore, for this application the distance from the primary shaft to the secondary shaft is less than 110mm and from the secondary shaft to the differential is approximately 125mm. The transmission with this layout results in a mass of about 38 kg. The dimensions and weight for the version with 310 Nm max. input torque are comparable with those of an equivalent single-speed unit (mass, 25 kg) from which this transmission was derived. A new version with input torque over 550 Nm is currently under development. Main parameters of such transmissions are reported in Table 1.

Example powerflows are shown in Figure 1.

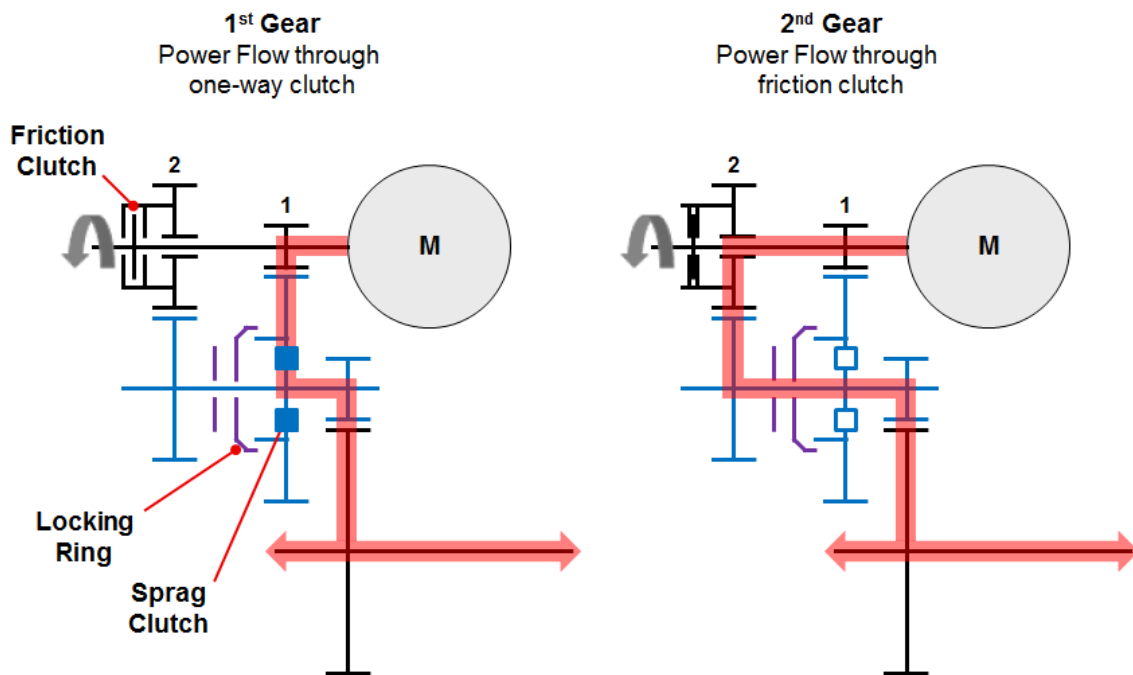


Figure1: General layout and powerflows for 1st and 2nd gear in the 2SED transmission

The design is mechanically very efficient, having only splash lubrication (no pump losses), and minimal number of gear meshes and bearings, with a two stage helical design.

Table1: Main characteristics of 2SED

Parameters		Existing prototypes	Under development
Max input speed	[rpm]	15000	16000
Max input torque	[Nm]	310	550
Abuse torque @ output (ABS, park lock, etc.)	[Nm]	6150	11000
Peak power	[kW]	210	320
1st Gear Ratio		15:1	15.6:1
2nd Gear Ratio		9.5:1	8.1:1
Weight (dry)	[kg]	~ 38	tbd
Oil volume needed	[l]	0.95	tbd
Clutch type		Dry (normally closed)	Wet (normally closed)
Actuation type (clutch and park lock)		Electromechanical	Electromechanical
Mechanical differential		Yes (open)	Yes (open/LSD)
Park lock functionality		Yes	Yes

2.1.1 The new electromechanical actuation system

Historically, controlled gearboxes have used hydraulic valves to move the actuators needed for mechanical movement of forks and clutches. This requires a supply of oil under a controlled pressure, accurate control of current in expensive solenoids, a high level of system cleanliness, close-tolerance machining on mechanical parts, and every mechanical interface must be sealed.

Creation of the high pressure feed is also a challenge. Past solutions may be divided into two groups - first, an electrically controlled motor (brushed or latterly brushless DC) with an accumulator to store a volume of fluid under pressure, and second a mechanically-driven oil pump directly producing a 'line' pressure.

The latter solution has always suffered from the need to be able to supply high flows to the transmission at low engine speeds, leading to a significant contribution to vehicle emissions. Further, there is too much flow at high engine speed leading to an efficiency reduction. It is only in very recent years that larger brushless DC motors (BLDC) have been used to control line pressure to assist with these issues.

On electrified vehicles with an ample supply of electrical power, it seems somewhat counter-intuitive to add a hydraulic actuation system when it could potentially be avoided. Taking a gear actuator intended to move a synchroniser as a typical example, the high-level requirements would be:

- Push force 800-1000N
- Total travel from 'Neutral' to 'In gear' approximately 8mm
- Time from 'Neutral' to 'In gear' will vary depending on the aggression of the shift. For a relaxed shift, a time of 300-500ms is typical. 100ms would be a 'fast' shift, and if the system is capable of supporting even faster actuation, so much the better.

It would therefore seem sensible to take these high-level requirements as a starting point to see if an electrical actuator could be developed to comply with them.

Small electric machines have been used for many years in conjunction with levers, worm gears, and fixed gear ratios to control gear forks and clutches on automated gearboxes – some with more success than others. The need for the additional parts to give sufficient mechanical advantage often means the packaging is compromised and costs can be high.

Figure 2 shows a brushless DC motor controlling both shift fork and the clutch in the previous generation of 2SED. In order to meet the force requirement and provide sufficient control accuracy, the solution needs a reduction ratio and a mechanical arrangement to have both devices actuated using the one motor. These additional components mean the actuation system as a whole is too high a proportion of the overall bill of materials for the transmission. So although this proposal is unquestionably a step in the right direction as it removes the need for at least 5 hydraulic valves, it cannot be regarded as the finished article.

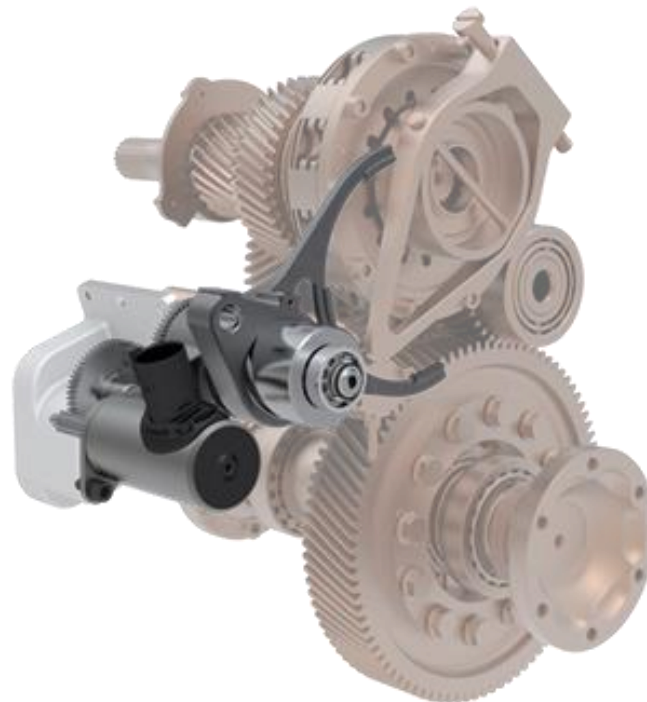


Figure2: 2SED with BLDC motor actuating shift fork and clutch

Keeping the hydraulic system high-level requirements in mind, a concept has been developed whereby linear actuation of the selection sleeves can be achieved within the transmission casing. Such a scheme is as shown in Figure 3.

The arrangement may also incorporate a position sensor, and it is possible to fit the whole assembly in a volume scarcely bigger than that of a fork which would historically have been used to move the mechanical parts. This being the case, installation into most transmissions is easily achievable.

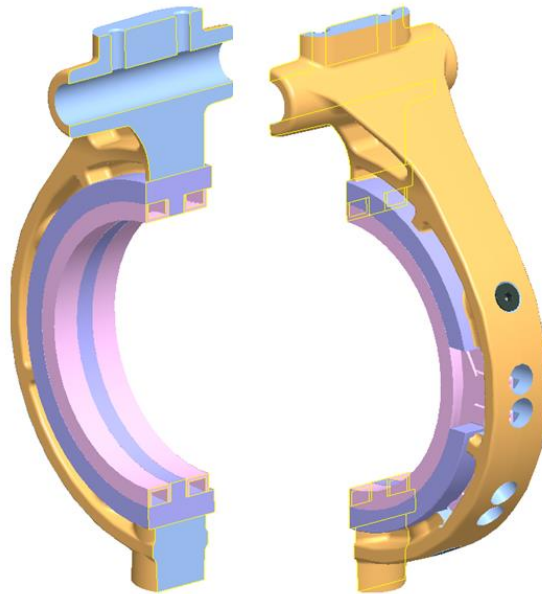


Figure3: Outline of the new electro-mechanical actuator

A real benefit of this approach is that the arrangement contains a minimum of moving parts, making it much cheaper than the BLDC motor equivalent, low wear, low maintenance, and the potential for higher reliability.

One key concern in this approach is in terms of the actuation speed, synchronisation force and controllability achievable when using coil currents and control methods sensibly available on-vehicle. As a proof of concept therefore, a test was developed to allow measurements using a representative test piece.

The results were obtained using a 12V electrical system, and if the maximum delivered current to the coils is kept reasonable (30A or less), it can be seen that for displacements of 4mm or smaller a force of 700-900N can be achieved. With the same current, at a displacement of 7-8mm the actuator can still provide a fair amount of force.

Speed of actuation must also be considered. In this respect, the electro-mechanical actuator greatly reduces the amount of time needed to move the sleeve from neutral to the in-gear position compared to a hydraulic-based arrangement. Results show that for a coil controlled at 30A actuation time is consistently in the region of 15ms.

The drive electronics chosen to control the coils was selected to allow the use of 12V, 24V or 48V as the supply. Work at the higher supply voltages is ongoing to characterise and control the drive and will be the subject of a future publication.

2.2 4SED

The 4SED has 4 gear ratios and utilises two traction motors, achieving power-shifting by supporting gear shifts on the alternate motor, keeping the mechanical design as simple and elegant as possible. This gives rise to 7 gear combinations (4 single gears and 3 dual gears), and is a cost effective solution for the automotive market with the omission of clutches and synchronisers.

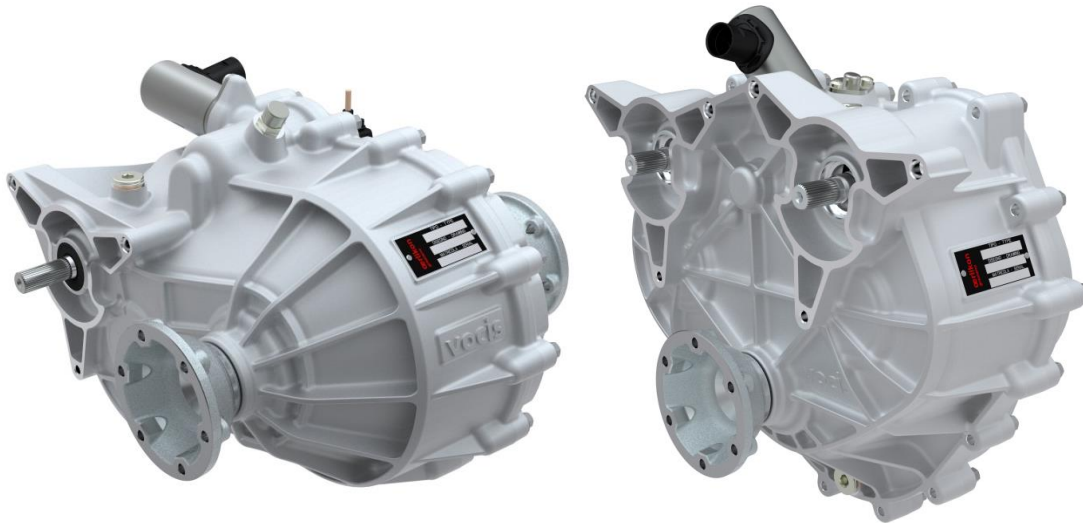


Figure4: 4SEED transmission with different electric motor locations









		Common Input Shafts
		Common components on Intermediate Shafts
		Common gear-select actuation system
		Common Differential

Figure5: The 4SEED design showing the assembly for opposing motor design on the left and the parallel design on the right, highlighting the commonality of parts between the two designs

The design is also modular, achieving not only scalability but also the ability to have the motors located at opposite ends of the gearbox or parallel to each other (see Figure 4), giving ultimate flexibility for vehicle

installation. The design has been configured such that the opposing motor design can be split down the centre of the transmission and the two halves used in the adjacent motor configuration with identical gears, shaft geometries and bearings. Having the motors on the same side of the gearbox also makes this configuration advantageous in terms of a very low axial length.

The control system is arranged such that driving torque can be sustained on one input motor whilst the second motor is disengaged during the gear change (see also Figure 6). The second motor may then be used for synchronisation of the new gear, switching its regime from torque control to speed control mode.

As a result, the concept:

- has neither clutches, nor synchronisers
- requires no hydraulics
- uses direct-acting, non-contact, electro-mechanical actuator devices, as described in the previous paragraph

A clear outcome of removing the synchronisers from the transmission is that the gear engagement now only involves dog clutches. On the assumption that the two sides of the dogs are synchronised and there is no dog-to-dog contact requiring a re-try or a push and twist strategy, then the required engagement force is minimised. It only needs to displace the mass of the engagement sleeve into the engaged position in an appropriate timeframe.

If the assumption regarding the dog engagement is always the case – i.e. that the electric motors do provide a stable synchronisation of shafts in a timely fashion - it is perfectly valid to size the electro-mechanical actuation of the engagement sleeves to only meet this lower force requirement. This significantly reduces the amount of coil current that is required in the actuators and their drives.

Therefore, the question is whether it is possible to always ensure that synchronisation is achieved and there is no dog-to-dog contact. This requires that the shafts are not only synchronised, but also aligned with respect to each other. This is achieved with angular control techniques already developed and proven in series production dual-clutch transmission control, which have been now implemented again in terms of dog engagement control.

Example powerflows through the 4SED are shown in Figure 6, with the layout shown being for the motors in the parallel configuration.

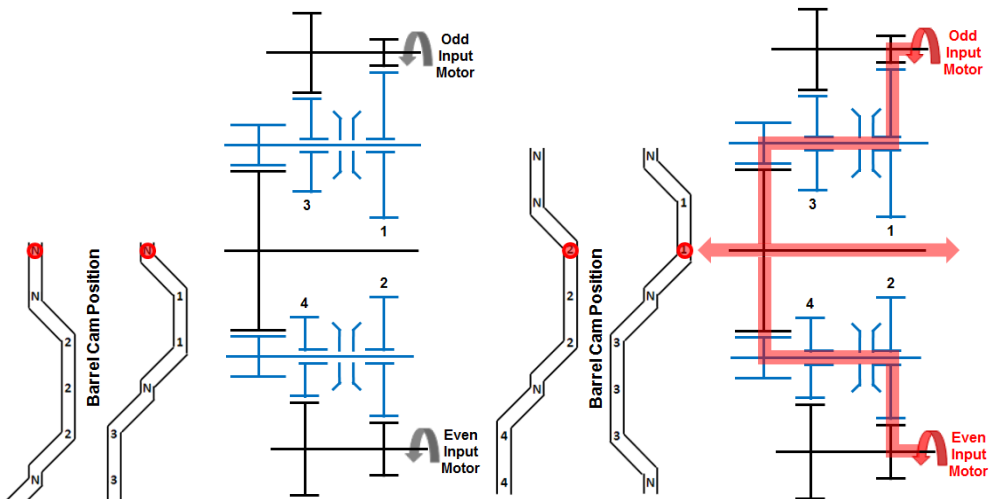


Figure6: Example powerflows through the 4SED, including barrel cam position for gear actuation. Left: shows example of neutral, Right: shows driving in 1st and 2nd gear together

2.2.1 Demonstration vehicle

A 4SED prototype is currently fitted in a demonstration vehicle (Mercedes Vito Minibus) driven by two 35kW peak power electric motors, which apparently appear undersized for such a vehicle that has an unloaded mass of 2200kg; however the 4SED performs more than adequately for demonstrating the power-shifting concept and how the torque between the two motors is handled during normal driving and the shift events.



Figure 7: The 4SED transmission in the Mercedes Vito minibus demonstrator vehicle

The main characteristics of the 4SED transmission prototype are reported below

- Max. power: 2x 35 kW
- Max. torque: 2x 75 Nm
- Max. input speed: 15.000 rpm
- Total transmission weight: 24 kg
- Splash lubrication

The results of the efficiency improvements will be presented in the next paragraph.

3 Efficiency benefits and cost evaluation

The demand for more speeds comes from the efficiency variability at different speeds; electric motors operate at a peak efficiency of around 90% but this can fall to 60-70%. Therefore multiple ratios can keep the traction motor at a higher efficiency for a wider range of operating torques and speeds. Different studies on efficiency improvements for multi-speed transmissions for electric drives were already published in the past, as i.e. in [1] and [2]. Internal analysis performed at Oerlikon Graziano have been showing an expected improvement of 8% for the 2SED over the NEDC cycle, and of 15% for the 4SED.

As base of this analysis, Figure 8 shows the theoretical Torque-Speed envelope comparing 1-speed and 2-speed applications for a 70 kW traction motor with the 4-speed application with 2x35 kW traction motors. The electric powertrain specifications match those for the above mentioned Mercedes Vito Minibus. The 70 kW single speed application is from and equivalent Mercedes Vito vehicle with a single speed transmission. The area highlighted in red shows the area of operating efficiency above approximately 90%. It is possible to see how, combining the different available operating conditions, the red area is becoming larger increasing the number of available speeds.

While further analysis are still ongoing on real driving conditions, the main question remains whether the efficiency improvements can overcompensate the additional transmission costs necessary to add multiple speeds to an electric transmissions. A qualitative analysis is reported in Figure 9.

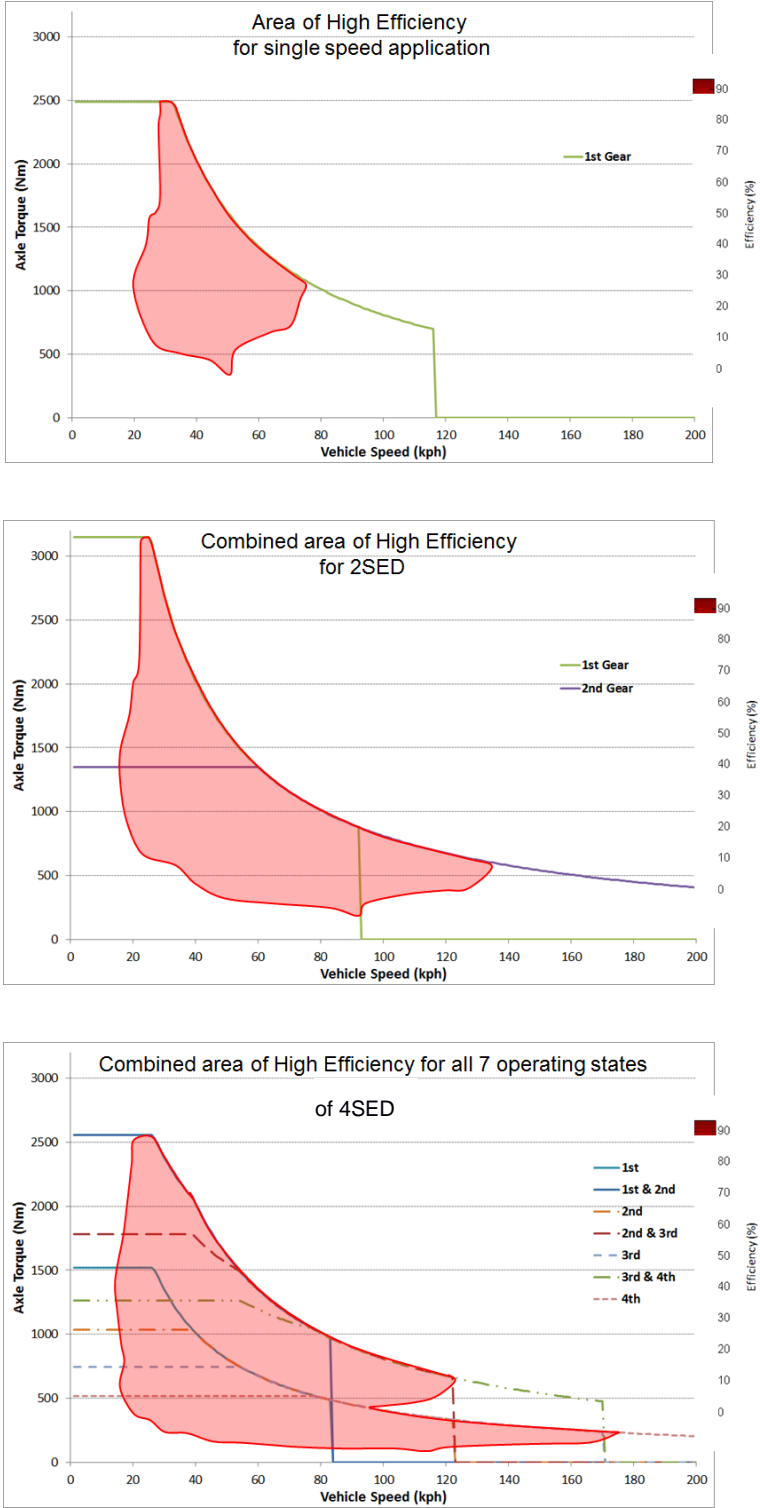


Figure8: Torque-Speed envelope comparing 1-speed and 2-speed applications for a 70kW traction motor with the 4-speed application with 2x35kW traction motors. The area highlighted in red shows the area of operating efficiency above approximately 90%.

The main contributor to potential cost savings is clearly the battery: the larger is the battery, the higher is the cost saving. For instance, considering a battery capacity of 40 kWh to achieve a certain electric range and an efficiency improvement of 15% by the utilization of a 4SED, 6 kWh battery capacity can be removed keeping the same range. This leads to a saving of 900 EUR, assuming 150 EUR/kWh battery cost. This approach can be extended to the power electronics and to the electric motor as well.

On one side, it is no longer necessary to use high torque electric motors to achieve the necessary wheel torque specified from the car manufacturers: the higher reduction ratio with the first speed allows the utilisation of smaller motors and/or cheaper motor technology. On the other side, less motor torque generally means reduced currents as well, with improvements on the power electronics costs. Moreover, different safety requirements linked to less extreme motor and electronics solutions can also contribute to improve the overall system cost. An analysis done on the base of currently running activities has shown an additional cost improvement coming from savings on power electronics and electric motor between 150-200 EUR, depending on volumes and type of application.

Finally, there are additional benefits as i.e. more flexibility in the powertrain design and calibration strategies, additional space left by reduced size battery, etc., whose value depends on the specific priorities of the different car manufacturers.

	Single Motor – Single Speed		Single Motor – Two Speed		Dual Motor – Four Speed	
Motor Cost	1off 70kW	→	1off 70kW	→	2off 35kW	↘
Inverter Cost	1off 70kW	→	1off 70kW	→	2off 35kW	↘
Battery Cost	Highest energy requirement	↗	Savings on energy use. Predicted -8% on NEDC *	↘	Max. saving on energy use. Predicted -15% on NEDC *	↘
Transmission Cost	Cheapest	↘	Increased, but still <10% of complete system	↗	Increased, but still <10% of complete system	↗
* Internal simulation study						

Figure9: Qualitative analysis of powertrain system cost variations as function of the number of transmission speeds

4 Conclusions

The multi-speed transmissions for electric drives described in this paper represent a concrete solution to support the requirements of future electric powertrains and the expected electric vehicle growth. Both 2SED and 4SED give a complete transmission solution for electric vehicles with improved economy and performance over more conventional systems. Additionally, the efficiency benefits can translate into overall electric powertrain costs being comparable or reduced in relation to a single speed application, making the multi-speed concepts presented here an appealing solution for many automotive applications.

Acknowledgments

The authors acknowledge the contribution of their colleague Marco Fracchia of the sister company Vocis Driveline Controls Ltd in the UK for the support associated with this work.

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Authors



Graduated at the University of Pisa (Italy) as Dr. Ing. in mechanical engineering, David Gagliardi started his career about 15 years ago at Piaggio Group in Italy, where he was part of the engineering team developing for mass production the first plug-in hybrid scooter of the world. In 2005 he moved to Germany to join Ricardo Deutschland GmbH, where he covered different positions and led the local Hybrid and Electric Systems product group. In 2014 he extended his experience overseas, joining the Hong Kong company Johnson Electric, where he was globally responsible for Automotive Drivetrain products. Since January 2016 he is Head of Business Development Automotive at Oerlikon Drive Systems Graziano in Germany, with global responsibility for Hybrids and E-Drives.



Graduated at the Politecnico of Torino (Italy) in mechanical engineering in 2004, Carlo Cavallino started his career at Oerlikon Graziano as Project Engineer, developing automotive transmission systems, as 4WD and DCT gearboxes for high performance cars. After an experience in Fiat Powertrain Technologies, he is now leading the advanced engineering group at Oerlikon Graziano, with main focus on powertrain electrification.