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EV Transmissions – Lessons Learnt

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Summary

Drive System Design (DSD) has worked on over 30 electric vehicle (EV) transmission projects over the past 7 years. This paper contains the main learning over that period. Included are insights into why transmissions are needed in electric vehicles and whether transmissions need to have single or multiple speeds. Also covered are common design issues including input spline fretting, methods for low noise gear design and powertrain mounting options.

Keywords: EV (electric vehicle); energy consumption; gear; powertrain; transmission

1 Introduction

The development of EV transmissions may at first have seemed to be relatively straightforward. Single speed systems were required that did not need shift systems or control. The electric traction motor would do all the work. Even for these simple transmissions, there were a number of challenges, especially in ensuring low noise. Since then we have seen an increased focus on multiple speed systems as data shows this can improve power consumption by between 8-18% (depending on who makes the claim and the shift system employed). These transmissions present new challenges as any gain in efficiency from using multiple speeds should not be comprised by an energy sapping shift system.

Drive System Design (DSD) has worked on over 30 EV transmission projects over the past 7 years and this paper will share the critical lessons that have been learnt whilst conducting this work. DSD have developed specific methods for the reduction of noise including system design (architecture) guidelines and targets for vibration and transmission error. The importance of motor excitation (radial, axial and torsional) will be discussed, along with the main considerations required in modelling such effects. The correlation of these methods to test data, and case studies showing the improvements made, will be shown.

The arrangement of the EV powertrain and how it mounts into the vehicle chassis is also an important consideration. Many earlier systems required large mount structures to meet traditional mounting points and these had a number of disadvantages.

Efficiency of EV transmissions is critical in minimising the power consumption. DSD have developed methods for ensuring maximum efficiency along with concepts for the management of oil distribution to reduce churning losses.

One of the more critical items in emerging transmissions is the best method for realising multiple speed transmissions. This paper explores the technologies used in a number of production, prototype and concept transmissions systems and proposes what criteria need to be fulfilled. It will also make recommendations for the types of shift systems that can be used to minimise the power losses from the gearshift while maintaining shift feel.

2 Why Do EVs Need Transmissions?

EVs require transmissions for four key reasons:

- Performance
- Efficiency
- To transmit power
- To optimise the system

By mapping the desired vehicle level torque-speed operating points into the e-drive capability envelope, the performance requirements for the e-drive can be determined. Since the size, cost and mass of an e-drive are mainly driven by torque requirements, there is a particular focus on implementing gear ratios to reduce the required motor torque. Faster motors are generally smaller, yet offer the same power.

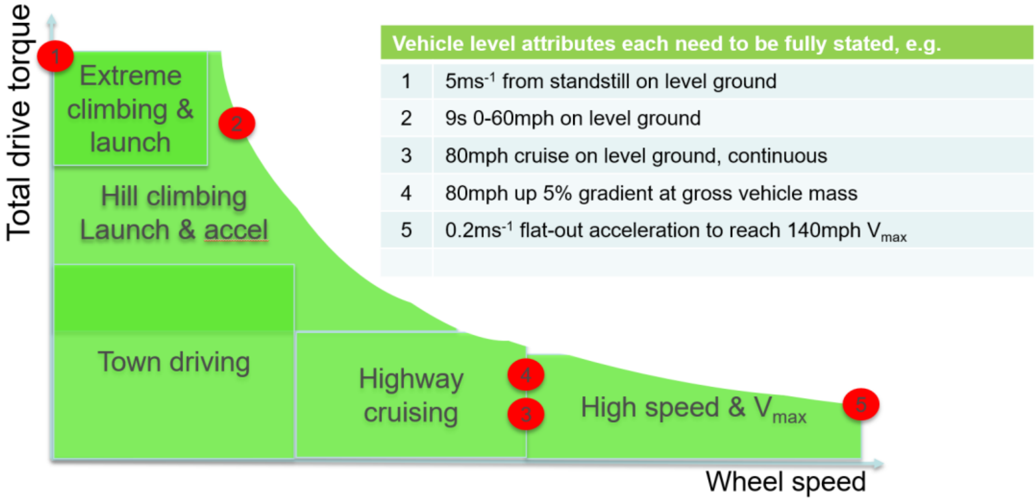

Figure 1: Mapping Vehicle Level Attributes

The efficiency of an EV can be improved through the selection and manipulation of e-drive operating points in order to minimise system losses.

Incorporating a transmission into an EV allows the e-drive axis to be offset non-concentrically and non-parallel to the driveline axis as well as providing the ability to torque vector.

A transmission allows the size of the e-machine to be reduced providing a smaller, cheaper and more capable system.

3 How Many Speeds Are Beneficial For an EV?

To compare powertrain solutions we will consider the case of a simple vehicle specification shown in Table 1. This allows us to determine the benefits and compromises of each system.

Table 1: Simplified Vehicle Specification

Vehicle	
Max torque	2,000 Nm
Max speed	100 mph
Torque at Max speed	300 Nm

3.1 No Transmission – Wheel Motors

A solution that doesn't involve a transmission is the use of wheel motors. This requires at least two motors that need to provide very high torque at low speeds. Since current motor technology is inefficient at low speeds, the range of these EVs are limited, as well as the high torque requirements, making gradeability and launch challenging. There can also be durability risks associated with wheel motors caused by high losses generating heat within them. However, they are not without advantages; they need only a simple development programme including only one motor and a relatively simple motor control system with torque vectoring as standard. The large diameter motors with a challenging design, limited performance and higher level safety cases due to having multiple motors, mean they are best suited to low performance applications that have priorities placed on cabin space. The main advantages and disadvantages are summarised in Table 2.

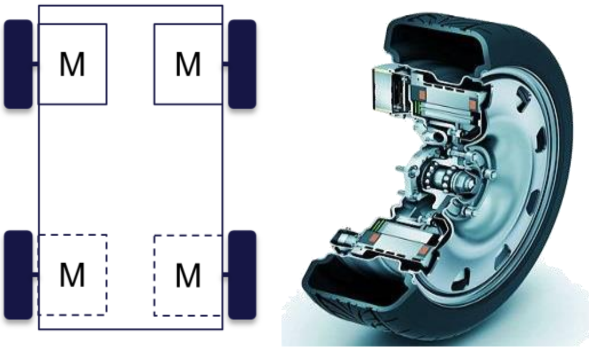

Figure 2: Wheel Motor Layout

Table 2: Wheel Motors – Advantages & Disadvantages

Advantages	Disadvantages
✓ Simple development programme = one motor and motor control system ✓ Control system not complex ✓ Torque vectoring as standard	× Multiple large diameter motors with high copper content × Challenging motor design × Limited performance and potential durability × Multiple motors require higher level safety cases

Using the Simplified Vehicle Specification we can see that to meet the requirements with only 2 motors we will need to output 1000Nm from each machine. This can be reduced with 4 machines but the torque level is still significant.

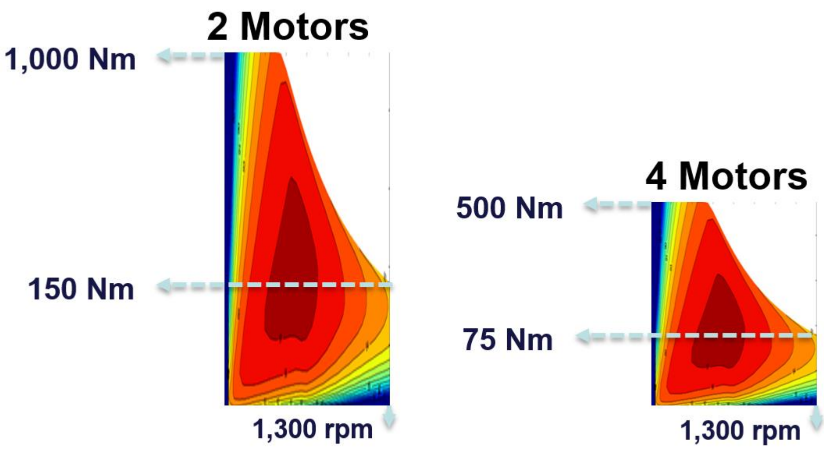

Figure 3: Wheel Motor Performance

For this reason wheel motor solutions are best suited to low performance applications where interior space is important. This could include vehicles such as autonomous pods which are being trialled in some UK towns and cities [1].

3.2 Single Speed Transmission

By using a differential, a single machine can be used per axle, allowing for multiple motor configurations and providing further opportunities for different performance attributes. Figure 4 illustrates various configurations and how package space is made more versatile by the transmission, allowing the motor to be mounted offset from the wheel's axis of rotation.

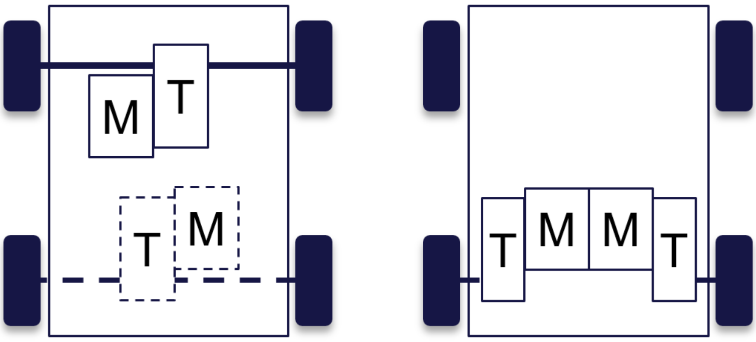

Figure 4: Singe Speed Transmission Layouts

The wheel torque provided is manipulated by the ratio used; this enables a smaller motor to be used for the same power. Two stage reduction ratios of up to 15:1 are achievable, enabling the motor to operate at speeds and torques where efficiency is optimised.

A single speed transmission requires development of only a single motor which can be smaller, lighter and lower cost for the same power as an equivalent system without a transmission. Additionally, the control system is not affected by the addition of a single speed transmission. However, there is an additional BoM cost and development programme for performance gains that can only be optimised in a limited range of operating conditions.

Figure 5 demonstrates the reduction in motor size through the use of a single speed transmission, reducing the requirements for the Simplified Vehicle Specification from four 500Nm motors to one 200Nm motor with a transmission ratio of 10:1.

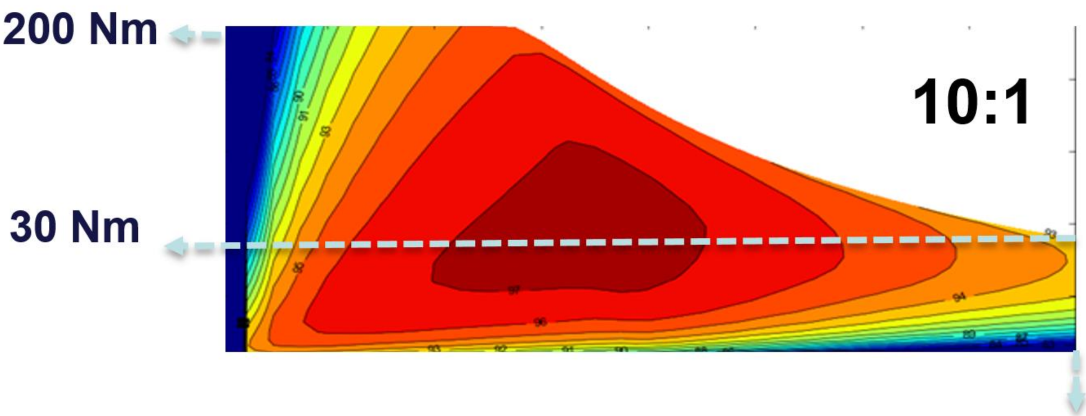

Figure 5: Single Speed Transmission Performance

Table 3: Single Speed Transmission – Advantages & Disadvantages

Advantages	Disadvantages
✓ Single motor options ✓ Smaller, lighter and lower cost motor for same power ✓ Control system development not affected by addition of transmission	× Additional BoM cost of transmission × Additional development programme for transmission × Performance only optimised in limited range of operating conditions

Most single speed transmissions are still aimed at 2WD systems for small to medium vehicles with a single motor delivering torque to each axle. However, the package is versatile and 4WD systems that use two single speed systems, one at the front and one at the rear, are now becoming more common. As the transmission can be concentric (using a planetary or compound planetary) or off access, there are various potential positions that can be used to meet package requirements.

3.3 Multiple Speed Transmission

Through multiple ratios vehicle performance and efficiency can be optimised for low end torque, top speed and mean operating conditions. The cost of adding additional ratios (>2) is relatively low compared to the cost of the development and manufacture of the actuation and control system. A more advanced control system is required to ensure that the motor is correctly controlled for shift synchronisation. Although there is an additional bill of materials (BoM) cost from the transmission, a smaller, lighter and lower cost motor can be used for the same power.

Looking at the Simplified Vehicle Specification, Figure 6 demonstrates the reductions in motor torque, and therefore size, possible using a multi-speed transmission. Figure 7 demonstrates the potential performance enhancements achievable using the existing e-machine from the single speed transmission example.

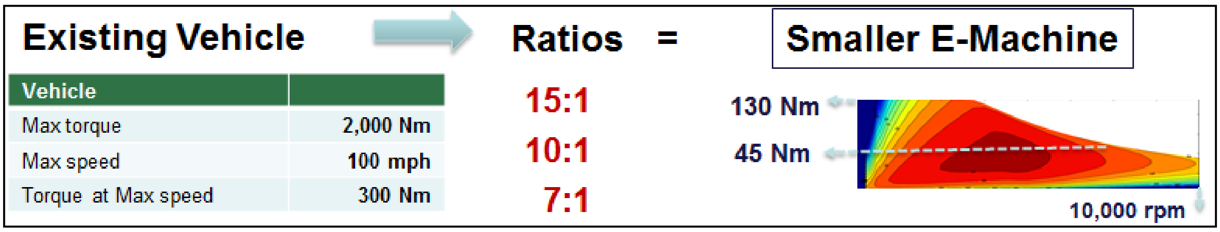

Figure 6: An illustration of how a multi-speed transmission would reduce motor torque requirements

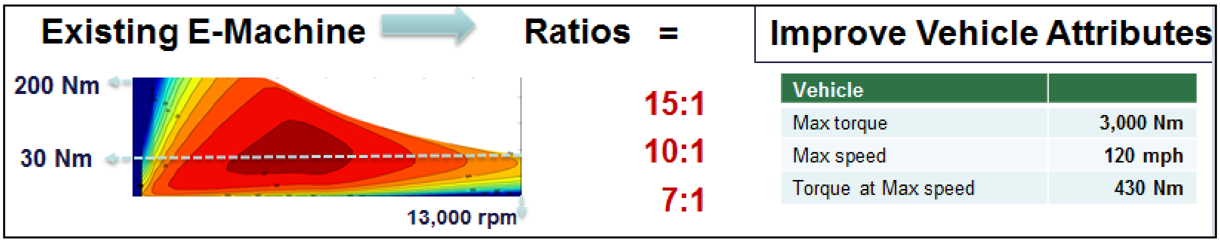

Figure 7: The performance benefits achievable through a multi-speed transmission

Multi-speed EV transmissions are useful in cases where an increased performance or efficiency attribute is required. For performance this could be: improved launch, top speed, off-road capability, or various special vehicle modes. Efficiency increases come from downsizing the motor and power electronics, in turn increasing the vehicle's range or reducing the battery capacity requirement.

There are different types of transmission: AMT, DCT, Automatic, Mechanical CVT and Electric IVT which can be considered for a multi-speed EV transmission. Deciding which of these is most suitable comes down to a series of criteria. Customer expectation is based on the cost, perceived refinement and popularity of single speed EVs. This dictates that multi-speed EV powertrains generally require powershifting for passenger car applications. Possible solutions therefore include an automatic, DCT or MSYS [2] style shift system. The advantage and disadvantages of multi-speed transmissions are shown in Table 4.

Table 4: Multi-Speed Transmission – Advantages & Disadvantages

Advantages	Disadvantages
✓ Single motor options ✓ Smaller, lighter and lower cost motor for same power ✓ Vehicle performance and efficiency optimised	× Additional BoM cost of transmission and actuation × Additional development programme for transmission, actuation and control × Motor control for shift synchronisation

There is no definitive answer to the number of ratios required, however with only 2 speeds the shift step can be up to 2.5:1 in order to optimise for launch and high speed. This large step is undesirable for shift comfort reasons. A step of approximately 1.4:1 provides more response and refinement to shifts. The inclusion of a third ratio allows optimisation for motorway cruising to be added increasing the time at maximum efficiency while having little impact on cost, transmission efficiency and development. Further reduction in losses require more innovative solutions.

4 Considerations for EV Shift Systems

When developing the transmission there are four aspects involved in producing an effective, competitive EV shift system.

Shift Quality: The shifting in an EV should be seamless, ensuring no torque interruption.

Drag: Drag within an EV shift system should have low losses comparable to that of a manual transmission.

In Gear Energy: No energy should be consumed between shift events.

Cost: Established technology should be used where available to minimise development risk.

These considerations were evaluated during DSD's development of the MSYS Powershift System [2] (for which the IP has now been transferred to Evolute Drives and renamed eVIE) which uses both a cone clutch to transfer torque as a friction device, and a dog clutch to lock the gear in place. The cone clutch allows seamless shifting, while the dog clutch latches the system to ensure that no energy is consumed between shift events. Figure 8 illustrates the layout of the eVIE (MSYS) system.

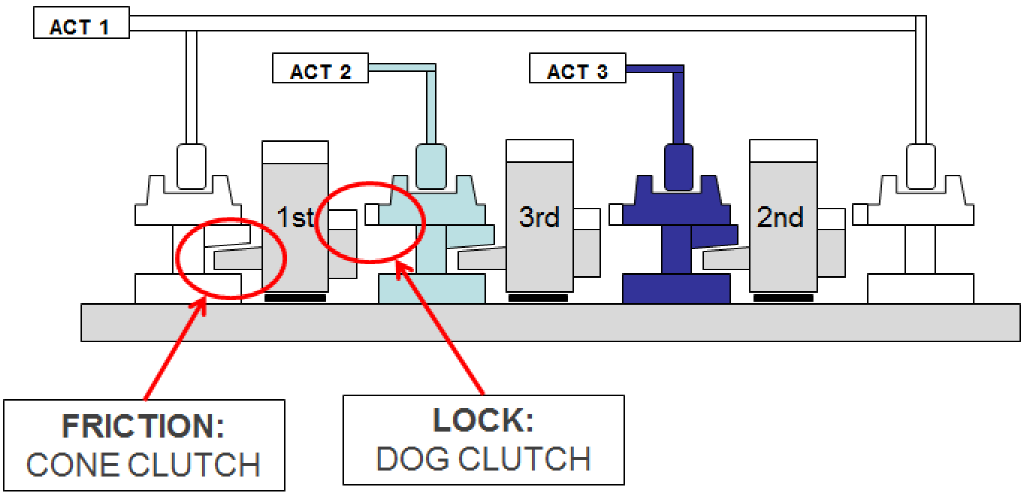

Figure 8: eVIE (MSYS) Powershift System highlighting cone and dog clutch

5 Efficiency & Durability

When designing an EV transmission, it is important to minimise bearing loads by keeping gear helix angles to a minimum, in turn allowing the use of high efficiency bearings. Mesh design is also important for high efficiency while maintaining low noise. Lubrication, both active and passive systems, should be carefully considered to minimise the losses to the fluid. DSD's previous work shows that going above 16,000rpm results in the need to evaluate forced lubrication systems. Actuation system losses for multi-speed transmissions should be minimised, for example in eVIE (MSYS) ensuring that no energy is consumed between shift events.

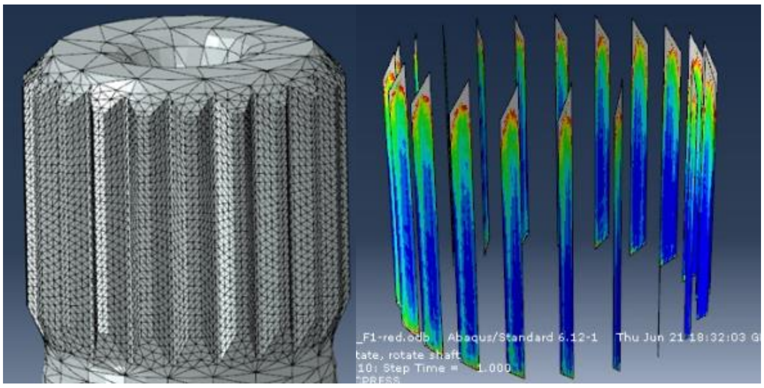

Figure 9: EV Transmission Input Spline Fretting Model

Spline fretting has been a common issue for EV transmissions. The input spline is in a dry location and consideration of constraints and tolerances are important in reducing the risk of fretting. DSD has generated spline fretting models looking at the effects of constraint conditions and misalignment for different loads. The key learning is that a location diameter near to the spline helps considerably in the reduction of fretting damage. To avoid interface and durability issues it is best to integrate the motor and transmission into a single electric drive unit.

Bearing durability, including shock loads cases, are more important where effort has been made to integrate low loss bearings such as ball bearings. For cases where high-speed machines are used the bearing speed limits must be considered for durability and friction losses. High motor speeds can also pose lubrication issues as well as high sliding speeds at the gear mesh.

6 NVH Optimisation

Since there is no longer an ICE, the allowable noise emitted from a transmission has reduced, placing more importance on NVH optimisation. Sensible gear mesh design helps achieve very low Transmission Error (TE) but must consider contact stress and efficiency. Casing design is another factor in trying to improve NVH, reducing modal response to excitation and modifying stiffness to move modes away from operating frequencies. Electric motors need to be considered when investigating NVH since they are an additional source of excitation, caused by torque ripple and radial vibrations. NVH optimisation is carried out by computer modelling and then tested to ensure correlation between the model and real world data. The initial step is to generate a full system model of the transmission including the gear, shaft, bearings and housing. DSD use MASTA software from SMT for this purpose. The model generates TE from the gear meshes, and torque ripple from the motor geometry. It then uses these to excite the transmission model. The vibration response is then measured at virtual accelerometer positions. This virtual measurement can then be compared to real test data to ensure correlation. Figure 10 shows the correlation of a transmission model of an EV transmission to test data.

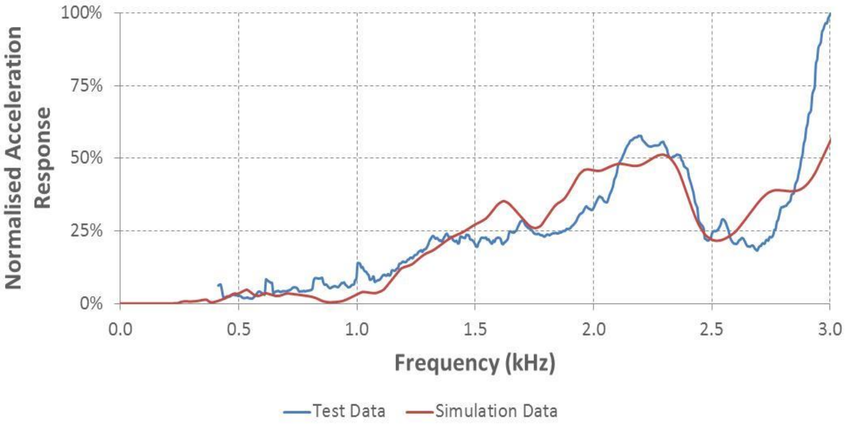

Figure 10: Correlation of vibration response calculation to test data

DSD has developed a method for the optimisation of the gear geometry; ensuring a design that provides low TE, low sensitivity to manufacturing tolerance, and the best possible durability and efficiency. This method has been proven many times and used to solve many EV transmission noise issues. Figure 11 shows the tolerance sensitivity analysis of an EV transmission gear set. It can be seen that the band of TE is narrow (dotted lines) compared to the nominal TE line (solid line).

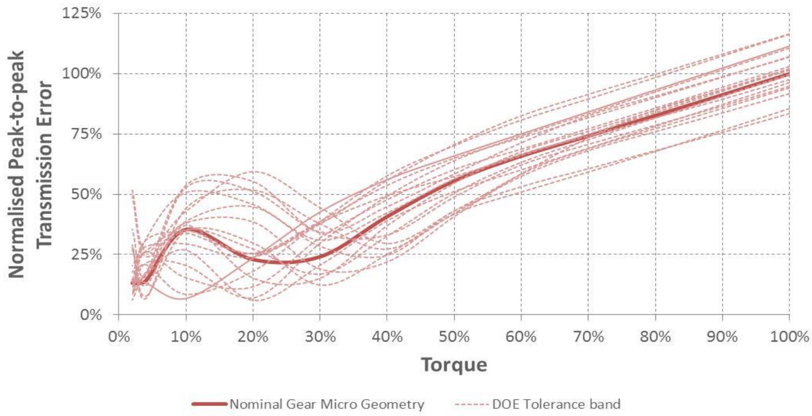

Figure 11: Transmission Error tolerance sensitivity analysis

Low noise in EV transmissions is not only a function of low excitation. Controlling the level of response is also important. Sensible design of the housing to separate system modes and distribute strain energy is also important. Figure 12 shows an example of a response analysis with optimised gear geometry, and a further analysis including an optimised housing. It can be seen that, by considering the housing design, the vibration level has been reduced to less than 50% compared to the original housing.

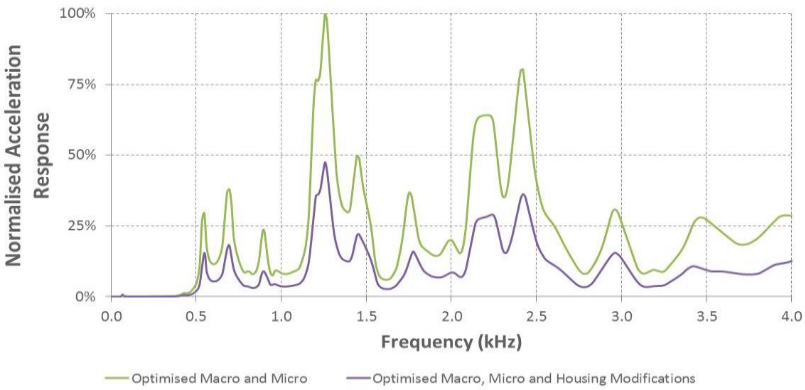

Figure 12: Effect of housing optimisation of reduction of response

The result of this careful design can be shown in an example from a project DSD performed on an EV transmission. The test measurement in Figure 13 shows the vibration measured on the housing, with a peak level of 481m/s². Following only 6 weeks of work, the optimised system with new gears and a modified housing was tested as shown in Figure 14. The result was a 98% reduction in maximum housing vibration to 10.6m/s².

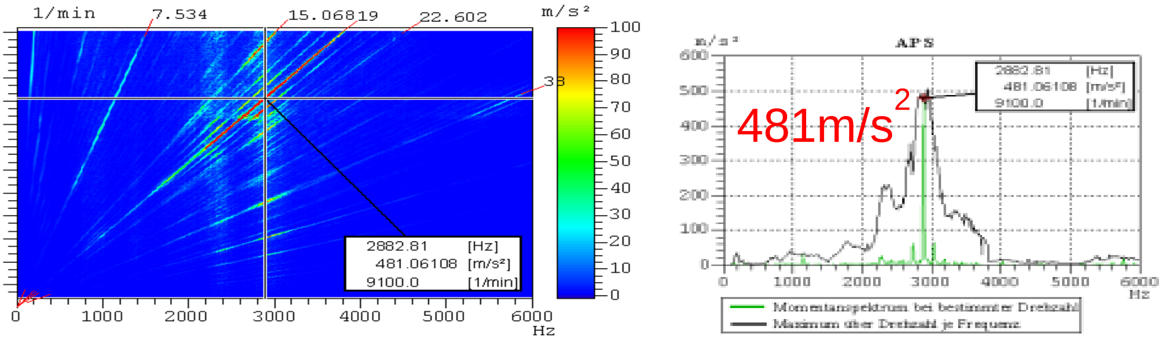

Figure 13: Original Transmission Vibration Measurement

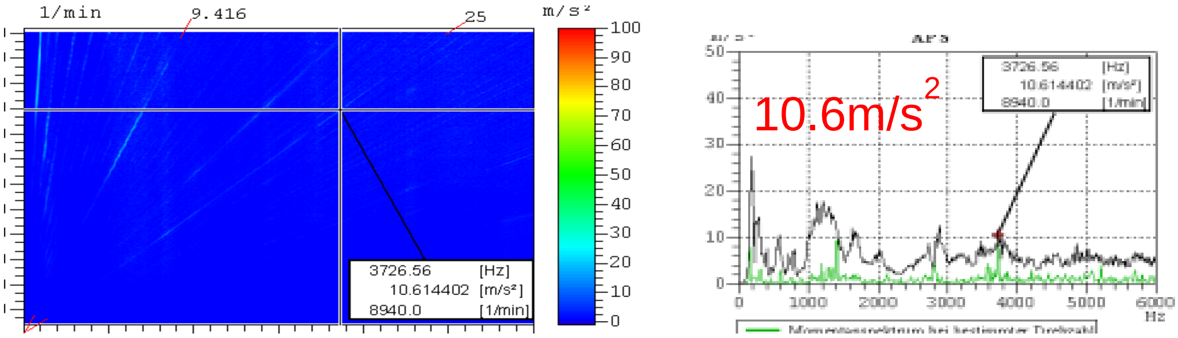

Figure 14: Optimised Transmission Vibration Measurement

7 Mounting Strategy

Mounting strategy can also be used to alter the noise behaviour of the system; wide mounts provide good transient and load reversal response, as well as meeting existing mounting positions. However, they require a very stiff, large structure to hold them in place that is at risk of vibration response in the critical 1-3 kHz region, as well as an airborne noise risk. Such a structure is given as an example in Figure 15.

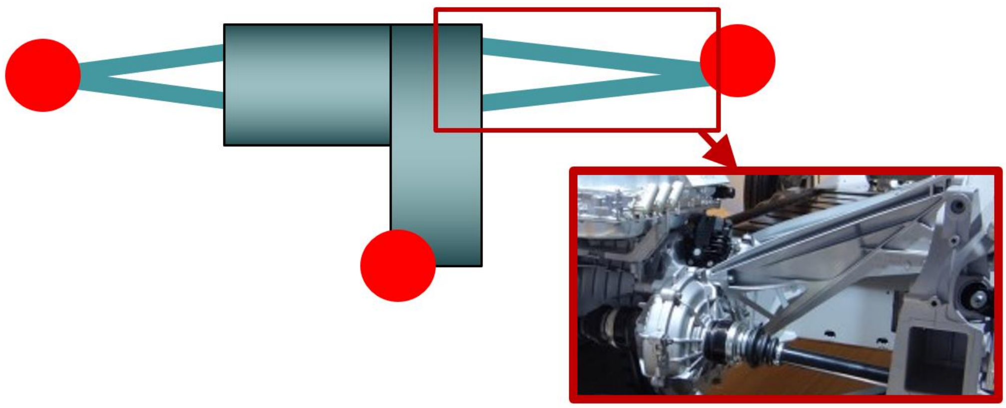

Figure 15: Wide mount solution for EV transmissions

Narrow mounts (shown in Figure 16) don't have the large structure but can be difficult to meet transient and load reversals, as well as the possibility of a structure borne noise risk being produced. In general the mounting strategy that is employed is dictated by package space.

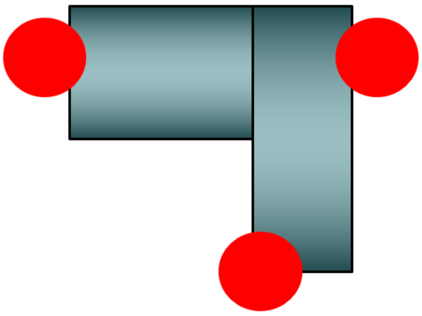

Figure 16: Narrow mount solution for EV transmissions

8 Conclusion

The lessons learnt from the work on EV transmissions have shown that the number of speeds required is dependent on the vehicle type. Small pod type vehicles are suited to having no transmission due to the tight space constraints while single speed transmissions are suited for modest applications. Multi-speed transmissions are best suited to more demanding applications. The shift system used in a multi-speed EV transmission must have low losses and be capable of powershifting between gears. Integration of the motor and transmission is better to avoid interface and durability issue. NVH is critical in the design of the transmission with consideration having to be made for the mounting strategy used.

Acknowledgments

Drive System Design would like to acknowledge all our customers and partners who have and continue to trust us to deliver world-class solutions for electric vehicle transmissions.

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Authors

Alex Tylee-Birdsall graduated from Imperial College in London in 1998 with a MEng degree. The majority of his career has been spent in automotive engineering consultancies exclusively in the field of transmission and drive units. As co-founder of Drive System Design Ltd in 2007, he remains a Director in the business. More recently he has moved his focus to the further development a multi-speed transmission system for Evolute Drives Ltd (as company that has spun out of Drive System Design Ltd).