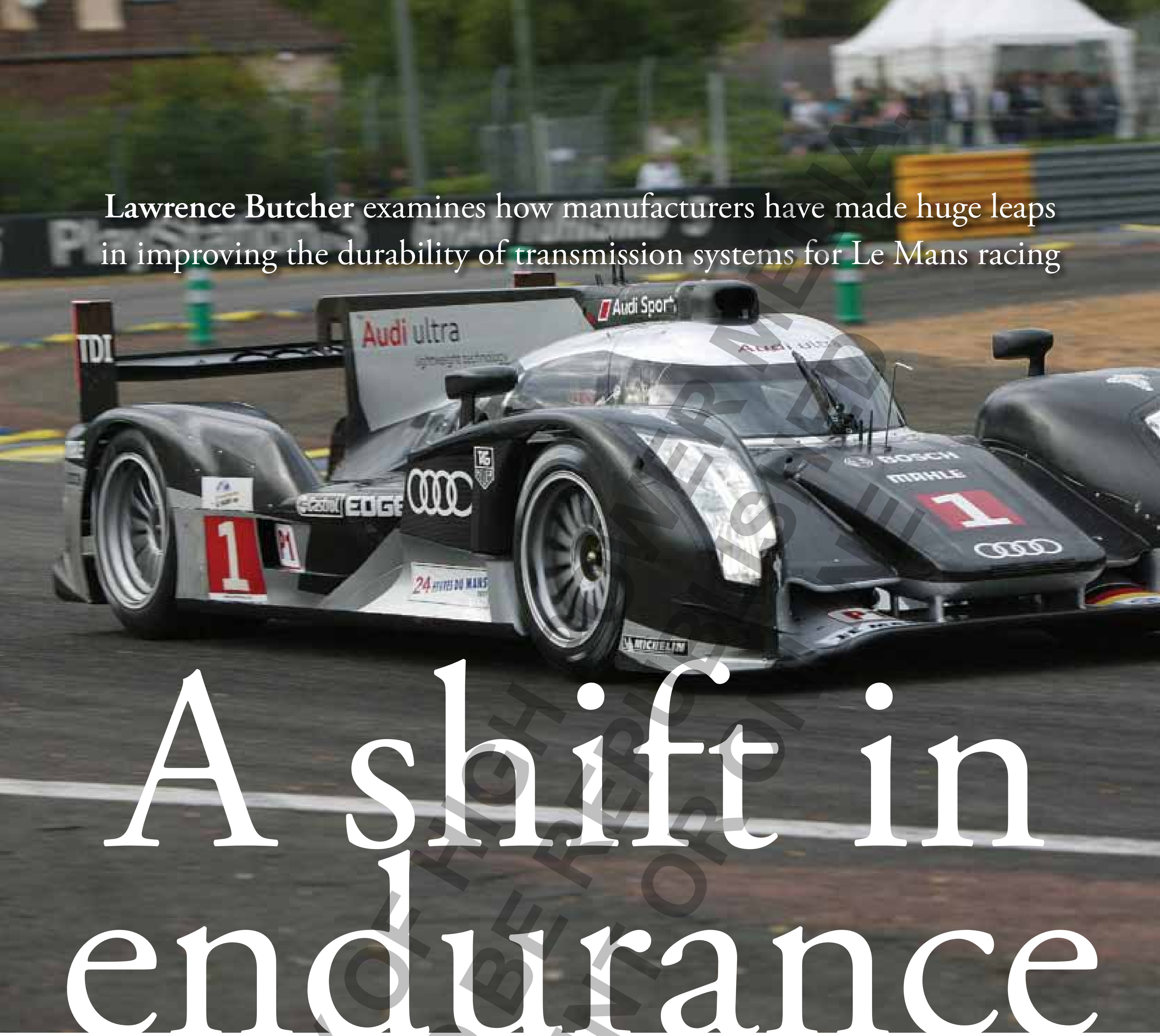


Lawrence Butcher examines how manufacturers have made huge leaps in improving the durability of transmission systems for Le Mans racing

A shift in endurance

Le Mans places abnormal demands on almost every component in a racecar, with the suspension and engine taking a relentless pounding on every lap of the 13.6 km circuit. Also subject to the same attrition is the gearbox and driveline, and in the past gearboxes were a regular source of problems for competitors, either through fatigue failures of parts or failures due to driver fatigue leading to missed gearshifts.

In recent years though, transmission failures have become far less common, thanks to a number of improvements in gearbox design, materials technology and gearshift systems. Ian Wight, business development director at Ricardo Engineering, which makes a number of transmissions for use at Le Mans, gives his take on the situation. "I think there was a definitive step-change when Audi started competing at Le Mans. Until then there were a lot of retirements from the race due to gearbox troubles, often in the closing stages of the day," he says. "With the development of the gearbox for the R8 though, a lot of work went into investigating what actually broke gearboxes, and from that stemmed a number of solutions which are now commonplace in endurance race transmissions."

In addition to design solutions specific to 24-hour racing, the overall direction of motorsport has seen transmission development veer more towards endurance, thanks to the appearance of many 'spec' and cost-controlled series. As Andy Scott, chief designer at Hewland Transmissions, explains, "All series at the moment – and the majority of gearboxes we make today are for series use – require a high level of durability from components.

"Le Mans is an exceptional set of circumstances but the criteria relating to the life of the box are the same: where you used to be able to get away with short-life boxes (in single-seaters and so on) and you didn't have the endurance requirement, they now command the same level of reliability and longevity as Le Mans boxes. For example, the GP2 series requires a similar life out of a gearbox as a Le Mans car; OK, they change the oil a little more often but essentially there is the same sort of life required on parts," he says.

In practice this means the internals of a current Le Mans-specification gearbox do not look fundamentally different from a regular 'formula' box, and the box has many of the same design features to aid durability. However, there is one area of technology

The transmission in Audi's R18 features a titanium casing housed within a carbon 'superstructure' that carries the suspension mounting points (Photo: Lawrence Butcher)

in which Le Mans is unique – the presence of large-capacity diesel-powered cars, capable of summoning unprecedented levels of torque, which would make very short work of the average transmission system. Beyond the diesels there is a plethora of different gearbox layouts, dealing with the demands of every type of engine from large-capacity V8s to small I4 hybrids. The categories see a mixture of designs ranging from transaxle layouts in front-engined cars such as the Corvette C6R, while the Prototype classes see both longitudinal and transverse gearboxes, from a number of manufacturers.

Internal layout and gears

While most manufacturers are not willing, or permitted, to divulge the secrets of their winning transmissions, some information regarding their layout and operation is available. In the Le Mans Prototype categories, both inline and transverse gear shaft layouts are used, depending on the specific packaging requirement of the individual car. Previously, a transverse layout meant a shorter casing, but several manufacturers have now created inline boxes with the same dimensions. The key to this has been in making the gear clusters and shafts shorter, thus increasing their stiffness and allowing the use of only two support bearings rather than the usual three. The result is a considerably shorter transmission, giving chassis designers greater flexibility in terms of weight distribution.

One of the biggest challenges in recent years has been in accommodating the vast torque of the diesel engines, which would have decimated transmissions designed to accommodate the output of petrol units. As Cliff Hawkins, development director at gearbox manufacturer Xtrac, explains, "A diesel engine not only has more torque but runs at lower revs and has a completely different delivery of power through the firing stroke of the engine, one which is more aggressive than a petrol engine, so it's a kind of double whammy

Most LM P1 gearboxes, such as this Xtrac 529 unit, are of a transverse layout, allowing for more flexible packaging in the chassis (Courtesy of Xtrac)

really. The reduced revs means that the speed to the cluster is often lower than with a petrol engine, but this can be addressed by the choice of ratio for, say, input bevels and final drives."

One breakthrough was the discovery that the strength of the dog gears could be increased more effectively by increasing their diameter, as opposed to their thickness. While this does increase the inertia of the gear cluster, it is more efficient than adding extra material laterally. Initially the increase in size of the internals, combined with the fact that the torque available from the diesels would allow for longer ratios, meant that the first diesel Le Mans Prototypes managed with five ratios instead of the usual six. However, the change in engine regulations to limit the capacity of the turbodiesels to 3.7 litres has seen the peak torque of the engines greatly reduced; where the previous engines were producing anything up to 1600 Nm, the new smaller-capacity motors produce nearer to 1000 Nm, and the power delivery is considerably higher up the rpm range.

This has meant that gearbox requirements have changed somewhat, in order to use the new power curve better. As one engineer in an unnamed team puts it, "One look at the power curve and once we'd drawn a graph of acceleration to top speed using a five-speed and a six-speed box, it was a no-brainer."

Other improvements have focused on the fine detail of components and, while beneficial for endurance racing, stemmed from other areas of development. One such area is in the design of shift forks. Most forks have a 'three pad' design where there are three points of contact between the fork and the baulk ring. One manufacturer found that it was difficult to keep the pads aligned during shifts due to flex in the fork, so after considerable FEA analysis the forks were redesigned with a two-pad arrangement, providing far more consistent performance. An offshoot of this development was a reduction in the force required to initiate a shift, thanks to the fork flex being harnessed to power the shift, reducing the load on the shifter system.

Coatings and finishing processes have also grown in importance, providing both friction reductions and increased durability of components. DLC coatings are especially useful, and are used to great ▶

effect on components such as shift forks and barrels, greatly reducing part wear. Gears benefit especially from the superfinishing process, with both wear and friction being measurably reduced.

Audi appeared at the 2011 Le Mans 24 Hours with a unique composite gearbox, where the carbon rear chassis structure also forms an integral part of the gearbox casing (Photo: Lawrence Butcher)

Casings

The gearbox casing plays a vital role in the structure of a racecar, as not only does it have to survive the significant loads exerted by race engines but, in the case of Le Mans Prototype cars, transmit a large percentage of chassis loads as well. On a Prototype, the gearbox casing will inevitably carry all the rear suspension mounting points, and essentially forms the rear section of the chassis, mounted to either a stressed or semi-stressed engine installation. This places great demands on the structure of the casing, which not only needs to be strong enough to contain the internal forces transferred from the engine, but also stiff enough to provide a responsive chassis platform.

Race gearboxes have traditionally been cast from magnesium or aluminium alloys, and this is still very much the case today. While Formula One has seen the appearance of composite, or hybrid construction gearboxes that use a combination of carbon fibre and exotic metallic parts, these developments are just beginning to reach Le Mans racers, and then only in the works-backed LM P1 cars.

Cast magnesium alloy is still the favoured material for casings, thanks mainly to its light weight and high fluidity when cast, which allows for thinwall sections to be achieved. Aluminium is ultimately stronger though. For example RZ5 magnesium, which is used in a number of sportscar gear casings, has a tensile strength in the region of 200 Mpa, while BSL169 aluminium alloy has a tensile strength of 240 Mpa when sand-cast. But MSR/EQ21 magnesium is seeing increased use owing to its improved properties at higher operating temperatures, thanks to the incorporation of a higher percentage of rare earth elements in its chemical composition.

The development of thinwall casting has seen aluminium gaining more widespread use. With advances in FEA analysis to allow for more accurate placement of material, the end product here is marginally lighter than an equivalent magnesium component. However, these casting techniques are considerably more expensive than those used for magnesium, so the cost/performance benefit is not always clear cut.

The fatigue properties of the two materials also needs to be taken into account, with aluminium being less fatigue resistant – in other words, more brittle – than magnesium. Given the repeated shock loadings the casings are subjected to, this has a considerable impact on component life. At the moment, neither material has a clear advantage over the other, as evidenced by Peugeot's use of a thinwalled alloy casing on the previous iteration of its 908 LM P1, yet choosing to return to a magnesium casing on its latest, 2011 car.

There are also a number of aluminium-magnesium alloys on the market that provide a good compromise between the two materials' properties, and several manufacturers have produced casings using these hybrids. Audi, on the other hand, has upped the stakes here, with the R18 featuring an investment-cast titanium casing housed within a carbon 'superstructure' that carries the suspension mounting points. This is about as advanced as sportscar casings get, and in the words of one observer, "It would probably have cost as much as the opposition's entire transmission budget." With the advent of hybrid systems placing further demands on overall vehicle weight, however, it is almost certain that even more exotic solutions similar to those found in Formula One – with casings built from a unified structure of composite and metal – will begin to appear.

Differentials

In the past it was not unknown for cars competing at Le Mans to run without differentials, using fixed spools instead. Driveability and performance were compromised, but it removed one more component from the list of parts likely to fail. However, modern limited-slip differentials allow for far greater control of wheel slip, while still proving reliable enough to endure 24 hours of racing.

Active differentials are not permitted within the scope of the ACO regulations, so considerable development has seen mechanical plate, viscous and hybrid viscous/plate differentials come to the fore. A viscous coupling on its own is purely speed-sensitive, and as a consequence requires a wheel speed difference across the axle to give any locking, so it is good on surfaces where there are different levels of grip available for each wheel. These differentials tend not to influence the car's handling when the differential speed across the axle is low.

Carbon-carbon clutches are the most commonly used variety in modern endurance racing, thanks to their exceptional resistance to heat and low wear rates (Courtesy of AP Racing)

A plate differential on the other hand is torque-sensitive and does not operate well on mixed traction surfaces; it needs grip to initiate a torque reaction, which in turn allows the ramp angles to induce locking on the friction plates.

To overcome or reduce the need to have equal grip on each tyre, a preload can be induced into the plate differential, but this in turn can lead to adverse effects such as understeer when there's little or no differential wheel speed. By combining a viscous and a plate differential you get the best of both worlds, and the plate differential can be set to have reduced or no preload, which is beneficial to the handling of the car. Previously, maintaining the performance of the fluid within viscous-type differentials proved problematic; however, closer manufacturing tolerances and improvements in fluid properties have increased the reliability of the units.

Differential development has also proved instrumental in effectively harnessing the prodigious levels of power generated by the diesel-powered cars. Although unwilling to say exactly how they operate, Ricardo's Engineering's Wight says, "The biggest thing for me on the diesel gearboxes is that when they appeared at Le Mans everybody said the torque would be too great to control. So we put a lot of effort into the differential design to harness this torque, and yet still house it all in a package that is the same size as a petrol unit."

Clutches

It would be fair to say that most clutches in endurance racing are of the multi-plate, carbon-carbon variety, although friction discs made from sintered material are still used. Carbon is the favoured material thanks to its exceptional resistance to temperature and its very low wear rate, with clutches being required to withstand many standing starts, thanks to the multiple pit-stops the cars complete (although they are spared a hard launch at the start thanks to the rolling send-off). Multi-plate clutches allow for a reduction in the diameter of the friction disc while retaining an ability to transmit high torque loads without overheating. Reducing the diameter of the rotating parts is beneficial in several ways, as it lessens the inertia effect on the crankshaft and allows the engine to sit lower in the chassis.

Despite the temperature resistance of the carbon material, clutches can still be damaged through overheating, while the aluminium clutch housing can deform at high temperatures and thus cause misalignment or failure in the mechanism. For this reason some clutches now feature housings made from titanium or metal-matrix composites, (provided they do not have an Ultimate Tensile Strength, or UTS, above 40 Gpa), which provide far greater resistance to the effects of temperature.

Driveshafts

Over the course of the 2011 Le Mans race, Audi made 31 pit stops, meaning that the driveshafts had to cope with 31 standing starts, transferring 600-plus bhp and nearly 1000 Nm of torque to the driving wheels. While this is the most extreme end of the spectrum, the repeated loads placed on any vehicle's driveshafts or propshaft over a race distance far exceed those experienced in any other field of racing.

The favoured materials for driveshafts are either high-performance steel or titanium, depending on the specific requirements of the car package. Invariably the shafts will be gun-drilled to reduce weight, and will incorporate tripode bearings at either end. This bearing layout is preferred because of its ability to operate more efficiently than standard constant velocity (CV) joints, with lower frictional losses. Tripode bearings can also be run at far more acute angles than standard CVs, allowing the final drive to be located lower in the vehicle. Where splines are used to locate joints they will be cold-rolled during manufacture, a process that creates less potential stress risers in the material than machining.

For front-engined vehicles that use a propshaft to transfer power to a transaxle, carbon fibre is the material of choice, providing exceptionally light weight with very high strength. The shafts generally feature either titanium or alloy joints, bonded into a filament-wound composite tube. Extensive use of FEA during the design of these shafts allows for the level of torsional flex to be fine-tuned providing, if needed, a degree of cushioning to the gearbox input.

As with any part of a racecar though, it is often the smallest component that can put you out of a race, and driveshafts are no exception. If the lubricant within the shaft joint is not contained properly then the joint will rapidly fail. To this end, seals and boots need to be specially designed to survive sustained use at high rpm and operating temperatures. Neoprene is the most commonly used material, providing good durability and temperature resistance combined with low weight.

Shift systems

Every engineer interviewed for this feature highlighted one key development that has made it easier to create durable gearboxes for endurance racing – the advent of semi-automatic shift systems that do not rely on the driver for accuracy. A driver can never be 100% consistent in the way they select a gear, and this places incredible strain on the teeth of dog engagement gears.

In the 1980s, Porsche tried to address this problem – with considerable success, it has to be said – through the use of synchromesh engagement on its sportscar gearboxes. While this increased the life of the gear sets, however, it also increased the shift duration which, if added up over a 24-hour race distance, accounted for a considerable amount of time lost. It was not until the advent of pneumatic shift systems in the late 1990s that truly reliable operation of dog engagement gearboxes was possible, with the level of sensor and computing technology making their operation practical.

As with many things in motorsport, pneumatic shifters originated in Formula One, with McLaren experimenting with systems in the early 1990s. However, these systems relied on immense levels of air pressure, in the region of 100 bar, which not only made sealing and reliable operation an issue, it also took a sizeable amount of power to generate these pressures. Tyrell made a breakthrough by developing a system that operated at far more manageable pressures of 8-10 bar. The idea of a low-pressure system was adopted by Megaline, which in turn developed a number of viable systems that could be retrofitted to a wide range of gearboxes, thus making rapid and reliable shifting available to the masses.

Unlike Formula One, the regulations laid down by the ACO specifically forbid semi-automatic or fully automatic selection of gears; however, there is sufficient room for interpretation in the rules to allow systems that guarantee accurate gear selection every time. The pneumatic shift system developed by Megaline consists of four main components – an electronic control unit with built-in compressor, a valve block, a shift actuator and hand controls for the driver. The most important component is the control unit, often referred to as the GCU. This interfaces with a number of gear position sensors within the transmission and with the car's ECU, and controls a number of operations such as throttle blipping and actuation of the shift mechanism.

Pneumatic actuators can be easily retrofitted to most sequential type gearboxes, with their compact size allowing for straightforward packaging (Courtesy of Geartronics)

On engines with fly-by-wire throttles the ECU interface can control throttle 'blipping', while on mechanical throttle engines the common pneumatic supply can actuate the throttle shaft. In the case of this system, a small compressor is also housed within the GCU assembly, simplifying installation; however, other systems are available that relocate the compressor, for example within the gearbox casing itself.

The relatively low operating pressure of the system means that sufficient system pressure can be maintained with only a small compressor, although other systems on the market, such as those produced by Geartronics, feature an accumulator that stores air above the operating system pressure, removing any possibility of missed shifts through lack of pressure. With these systems the air pressure is regulated as it is released from the accumulator. Distribution of the air is controlled by a valve block that directs air on demand to the actuator, which is linked directly to the gearbox's shift linkage.

The final part of the system are the hand controls for the driver, which invariably consist of two paddles mounted on the steering wheels, one controlling upshifts and the other downshifts.

The key benefit of this type of system is its ability to protect the drivetrain. While the regulations do not allow the controller to retry a gear selection automatically, they do allow it to limit factors such as re-application of the throttle before the dogs are fully engaged.

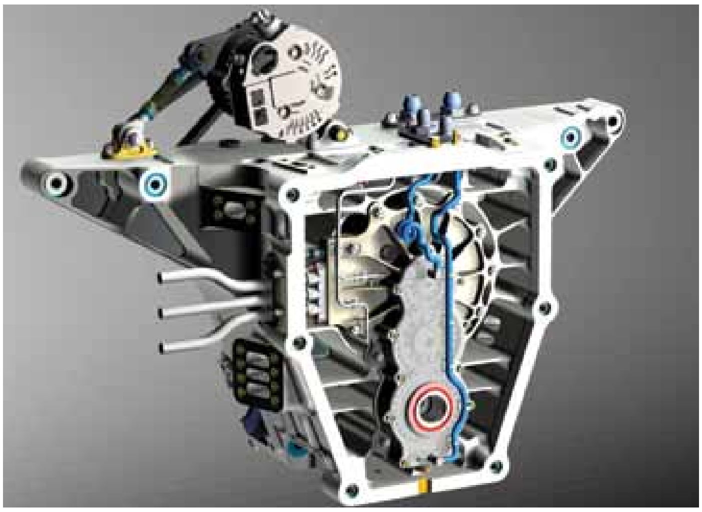
Another system available to teams is produced by Zytek, and replaces pneumatics with an electrically operated shift actuator. The control side of the system works in an identical fashion to a pneumatic system, relying on a combination of input data from gearbox, chassis and engine sensors. However, the actual movement of the gear shifter is completed by a push/pull electrical solenoid, powered by a high-voltage supply from the system's controller. The system can also accommodate non fly-by-wire throttle systems, with a separate solenoid controlling the throttle shaft to initiate a 'blip' on downshifts.

Both systems appear to be perfectly capable of completing accurate shifts, and have more than proved their worth, with each providing a different packaging solution. No system is infallible though, and this was highlighted during the 2011 race when the shift system on the Roberston Racing Ford GT, competing in the GTE Am category, failed. The incident proved an invaluable lesson in the benefits of having a back-up system, as fortunately the original, lever-operated sequential shift system had been left in place and some quick thinking by the pit crew saw the paddle shifter disconnected and the traditional set-up reinstated.

Fluids

The oil inside the gearbox needs to be able to stay in optimum operating condition for the duration of the race, where it will see extended periods of high-temperature running. Whereas normally oil would be expected to be changed after a few hours' use, this is not a viable option at Le Mans. This means lubricant suppliers need to make a trade-off between weight of lubricant and longevity – an oil that's too heavy will create greater parasitic losses, whereas if it's too thin it will not provide sufficient protection to the internal components.

To ensure reliability, gearbox and lubricant manufacturers go ▶



The Zytek KERS uses a series of drop gears and a clutch interface to transmit drive from the motor/generator unit, all of which is housed in a bespoke bellhousing (Courtesy of Zytek)

to great pains to maintain and monitor oil condition, with oil management playing a key role in the reliability of a transmission. The availability of sensors to monitor the breakdown of oil, and analyse particles within it, means that engineers have a far greater understanding of the state of the transmission throughout the race, and allows for early warning of potential problems.

Andy Scott of Hewland Engineering explains the steps the company takes in relation to lubrication of endurance gearboxes. “You tend to carry much bigger oil tanks, in case the worst should happen and you have a leak,” he says. “Oil conditioning is a big consideration, and all our recent gearboxes have both pressure and scavenge filters built into the gearbox. We used to rely on the teams and chassis manufacturers to provide them externally, but we now build them into the boxes, and although we have to rely on the teams cooling the oil, everything else is looked after by us.”

How the oil is controlled within the box is also an area of considerable development, with manufacturers developing more efficient ways to direct the lubricant to important areas, then scavenging it back to the tank.

The latest generation of Prototype transmissions are designed to be retrofitted with energy recovery systems, allowing teams to adapt to changing regulations (Courtesy of Xtrac)

Hybrid systems

While hybrids have seen action in sportscar racing in the past, 2011 has seen their full adoption within the regulations and the appearance of valid hybrid Prototypes. Two hybrid-equipped cars were present at the 2011 test weekend – one electrical, one mechanical – although only one competed in the race, the Hope Pole Vision Oreca 01 (discussed elsewhere in this issue), which features a flywheel-based energy storage system.

Both hybrid systems transmit their power through a connection to the main shaft, and are housed in custom-made bellhousings, allowing them to integrate with a wide range of engine and transmission packages. The flywheel-based system relies on purely mechanical-based storage of energy, using a system of discrete gears and a multi-plate clutch pack to transfer energy to and from the flywheel. These clutches perform a controlled slip to transmit the drive through the gearbox input shaft, with the gear ratio in the KERS system allowing for the stored energy to be released at different rates.

The electrical system, from UK manufacturer Zytek, is also housed in the bellhousing and connects to the gearbox input shaft. The drive of this system is much simpler than the flywheel, consisting of a number of drop gears and a clutch to transfer power from the motor/generator unit. With the likely increase in KERS-equipped cars, several manufacturers are now producing hybrid-ready transmissions as customer units, which can easily be retrofitted with KERS units.

Conclusion

Improvements in gearbox and general driveline technology have been of significant importance to the overall reliability of cars at Le Mans during the past decade. The biggest improvement has been in the area of shifter systems; by ensuring a consistent shift every time, the loadings and wear rate on the gear dogs is decreased massively, removing one of the key reasons for transmission failures.

The other key area of development has undoubtedly been led by the introduction of diesel power, and the ensuing mountains of torque, which has seen huge advances in the strength and durability of transmissions. The current generation of transmissions found in the works cars now package six gears into the space previously occupied by five, yet are capable of dealing with nearly twice the torque levels produced by even the most powerful petrol cars.

With the regulatory emphasis moving towards hybrids, the next challenge facing transmission engineers will be incorporating, where necessary, the required additions to the drivetrain, without compromising the overall package or adding excessive extra weight. This constant quest for reduction in weight and size will undoubtedly see the adoption of more methods and ideas spawned in Formula One, with fully composite gearbox casings and ever-smaller gear sets becoming commonplace. And if fully electric cars ever make it to Le Mans then a whole new era of endurance racing transmissions will begin. ■