A 4wd gearbox designed for use in the Super 2000 rallying class. Note it is a transverse design (Courtesy of Xtrac)

Gears of war

Lawrence Butcher examines the demands facing rally transmission designers, from materials and construction to operational and packaging requirements

It is unlikely that any type of competition vehicle is required to deal with as wide a range of conditions as rally cars and off-road racers. The cars (and drivers) face a combination of punishing terrains, extremes of environment and less than ideal servicing facilities. This means that components designed for use in this sphere of competition must fulfil a number of exacting requirements for durability, functionality and ease of maintenance.

Transmission components are no exception to this rule. Not only do they have to fulfil the mechanical task of providing drive to either the front, rear or all four wheels, they must also be durable enough to operate in harsh conditions and allow for easy servicing and adjustment between stages – requirements that also apply to other ancillary components such as differentials.

Evolution of the WRC regulations

To begin with, it is pertinent to look at the premier class of rallying, the WRC, which stands at the top of the global rallying hierarchy. However, it is fair to say that the championship does not represent the peak of technical innovation that it once did. The economic woes of the past few years have resulted in a drive towards cost savings, which has in turn impacted on engineering freedom. Ten years ago, WRC cars were far removed from any other type of current rally machinery, but with the introduction of new technical rules in 2006 and Super 2000-based regulations in 2011, the complexity of the designs manufacturers can use has been greatly reduced.

These latest rules relate to the technologies and materials that can be used, and the level of deviation allowed for component location in relation to the base roadcars. Additionally, like many other racing formulae, the top ranks of rallying have also seen the introduction of strict cost regulations, going beyond the scope of simple technical rule changes.

For transmissions, these encompass not only the price a transmission can be sold for, but also spare parts prices and the number of events a specific unit must be used for. Further to these flat rates, FIA regulations for Super 2000 and WRC also require homologation of the transmission, meaning that once the transmission is approved no changes are allowed without the car's manufacturer using a 'joker'. A joker is a one-off exception to the homologation specification; teams have a set number of them to fall back on each season. They can be used to rectify reliability issues but, being racers, they would much rather use them for implementing performance upgrades.


Helical gears with dog ring disengaged in the neutral position (Courtesy of Albins)


Helical gears with dog ring shifted to engaged position. Note how during rotation the dog gears will mesh and drive will be facilitated (Courtesy of Albins)

The impact these regulatory changes has had on the complexity of cars is considerable: it has seen the demise of a number of performance-enhancing components, most notably the use of centre differentials on the propshaft, and the banning of active differentials (though these are still allowed in other classes at a national level across the world). The regulations give designers far less scope for development, and have resulted in some fundamental changes in gearbox design.

When the regulations were less restrictive, gearbox layout and location was an area where considerable extra performance could be gleaned. A transverse engine and transmission layout is near-universal in most mainstream production cars of the types used for rallying. In the past, designers found benefit in rotating what was originally a transverse gearbox through 90º, when converting them to four-wheel drive. This put the gearbox and centre differential of the car's four-wheel-drive system in line with its longitudinal axis; in turn simplifying the drive to the rear differential. This approach also moved the mass of the gearbox further aft, with consequent benefits to handling balance, so as a result many WRC manufacturers took this approach.

However; these changes were not without complications, notably the need to create a transverse transfer case running across the back of the engine, increasing weight and complicating packaging issues – not to mention costs – for what was ultimately only a small improvement in handling balance. Over time, designers discovered that a similar balance could be achieved through careful design of a transverse layout, a solution used in all the current generation of WRC cars.

The introduction of the smaller, 1.6 litre forced-induction engines into the WRC has also had a knock-on effect on gearbox design. The wide power band of the previous generation of 2.0 litre turbocharged engines meant only five gears were deemed necessary, with some manufacturers even experimenting with four speeds. With the

A standard helical-cut dog gear with the 'dogs' clearly visible (Courtesy of Albins)

reduction in torque brought about by the smaller engines, the latest generation of WRC cars are exclusively six-speed. As a point of note, the 2013 WRC regulations allow a competitor to homologate either one final drive ratio and two sets of gear ratios, or two final drive ratios and one set of gear ratios.

Within the framework of these constraints on cost, reliability and a lack of opportunity to develop parts once homologated, the focus of transmission manufacturers has been on finding the best compromise between performance and cost. The key factors governing this approach are ensuring consistency of components and assembly, combined with a design that achieves the required minimum weight, while also staying within the cost constraints. This has led some manufacturers to develop very specific validation systems for each transmission: every sub-assembly is pre-tested before assembly into the whole transmission, which is in itself then subjected to a build sign-off test to a predetermined set of parameters relating to the oil system, the gear change and the differential performance. One manufacturer has even gone so far as to develop its own duty-cycle FEA simulator specifically for rally transmissions to ensure that new designs will be reliable from the off, and resilient to the extreme demands they will see in use.

The rally environment

The environment a rally transmission inhabits is uniquely challenging and, with the possible exception of Paris-Dakar type racers, they are subject to some of the most extreme forces in motorsport. Situations such as transitioning from low- to high-grip surfaces can shock-load the gearbox and driveline, while the environmental conditions present problems that are rarely, if ever, encountered in circuit racing. Consequently, rally-specific transmissions will have additional features over similar circuit racing designs in order to ruggedise them, for example the gear shafts and bearings will require uprating over circuit cars with similar power outputs.

It is not just the physical punishment of a rally stage that needs to be considered, but also the prevalence of dirt and detritus that can find its way into every nook and cranny. Service time is limited on stage rallies, and problems such as dirt ingress into fixtures and fittings can severely hamper service crews' tasks.

One manufacturer questioned for this article explained that problems in servicing become less common by ensuring that there are no obvious dirt traps within a component and that the mountings are sufficiently accessible to allow easy mounting and dismounting as well as oil filling and oil level checking. In the WRC, transmissions are sealed units, which are not dismantled or serviced during an event, procedures which only take place in a clean workshop environment. However, several manufacturers highlighted the importance of ensuring components such as oil hoses can not be accidentally damaged while other components are being serviced. Sealing of orifices such as driveshaft inputs also needs to be more rigorous than in other racing environments, with the addition of features such as steel seal carriers being normal practice.

The lubrication requirements of a rally transmission also differ from the norm, thanks to the range forces a car is subjected to. In addition to the usual cornering and acceleration forces, significant vertical movement can also come into play, as any average forest stage will testify. To ensure lubricant is always present where it's needed, baffles are generally incorporated into the gearbox structure to control oil flow around the interior. One producer of WRC transmissions has even gone to the extent of developing a gimbal test rig, which can accurately simulate the gyrations a transmission will go through in use. Full data logging of the lubrication parameters during testing then allows engineers to develop a map of the oil's movements during acceleration events and assess the effectiveness of the oil control systems.

Gear engagement

It is almost universally the case that transmissions for top-level rallying are transverse in orientation and use a sequential shift pattern with dog engagement on the gears. A sequential shift transmission only allows gear selection in a sequence – so, for example, the driver cannot shift directly from 5th to 1st; they must run down through the intermediate ratios.

Gear engagement is facilitated by numerous large teeth (dogs) that mate into matching openings machined into the opposite surface of the driven gear. Unlike a synchromesh engagement, the two rotating gears are operating at different speeds (unless the revs have been matched) and there is no synchronising mechanism to help bring them up to a synchronised (equal) speed. Ideal gear selection to minimise clashing and wear of the dog rings is achieved by a momentary break in the engine's driving load until the shift is completed. This is achieved by a quick throttle reduction, ignition cut/retard or clutch ▶

The best quality and strongest gear teeth are ground rather than cut (Courtesy of Albins)

depression. (The opposite is true of a synchromesh gearbox as used in passenger cars, where slow movement helps to allow the synchros to match shaft speeds). When timed properly with practice, the gear selection can be very rapid, of the order of milliseconds.

The number of dogs and the size of the openings into which they locate determines the window of opportunity the dogs have to engage during a shift event; several transmission manufacturers consulted for this feature felt that a smaller number of dog teeth offer a better shift quality. However, the use of fewer dogs does lead to increased noise and abruptness on the shift. While the noise is not a major issue in a competition environment, the forces generated by an abrupt shift can place extra strain on other components. Each manufacturer will have its own unique dog geometry, which it feels is the best balance between performance and durability.

If the dogs do not line up sufficiently during a shift event to facilitate a gear engagement, the faces of each opposing surface (dogs) will clash and, over time, can wear. This wear will depend on the speed of the dogs and the force applied. To counter this, some gear manufacturers implement a 'pent-roof' pentagon-shaped surface to deflect apart the dogs on a mis-shift. This drastically enhances dog gear life.

It should be noted that there is minimal wear on the dogs when they are fully engaged – that is, the car is in gear. Damage can only take place when initiating contact during a shift, therefore this event must be made as short as possible. Problems will generally only occur if the driver moves the gear lever slowly, or if the linkage is poorly secured. It is also worth mentioning that some dog wear is inevitable, but a driver's shift 'style' among other factors will have a bearing on the amount of wear experienced.

Gear manufacture

Although designed for tough conditions, the gears used in transmissions destined for rally use are essentially the same as any competition-specific units. Most high-performance transmission manufacturers produce gear sets from high-quality steel billets, and it would be fair to say that many manufacturers use very similar materials, thanks to the fact that there are a limited number of steel producers globally who refine the high-alloy steels required. There are exceptions to this rule though, and some companies possess their own in-house formulae developed in conjunction with steel suppliers. The production processes differ considerably between gears intended for mass production and those designed for the demands of competition use, the biggest difference being that traditional high-volume manufacture tends to use forged blanks for gears, whereas competition components will tend to be CNC-machined from billets.

The cutting will usually be undertaken using specially designed and precisely ground tooling, in order to achieve very close tolerances on complex tooth profiles. Poorer quality gears are often manufactured using off-the-shelf tools to save on costs but which compromise tooth strength. Also, any misaligned or poorly machined parts will drastically affect the performance and wear characteristics on dog engagement systems. By contrast, tolerances on synchro engagement systems are much more forgiving due to the slipping of the brass cones.

Tooth design is critical to power-holding capability, and the design itself requires that a number of factors be taken into account, including (but not limited to) gear ratio, tooth count and load paths through the gear shafts. In the very highest performance applications, even CNC machine cutting is not sufficiently accurate, instead gears will be ground to shape. This process involves the use of extremely accurately shaped grinding wheels that form a 'negative' of the gear tooth profile.

Grinding has a number of advantages over traditional machining methods. First, a cut gear must be heat treated after cutting, which can introduce measurable distortion, negating the precision tooth profiles. Grinding, however, takes place after heat treatment and thus gives a finished part with much closer tolerances. A second benefit of grinding is that it allows for gears and shafts to be made as a single component, which is not always practical due to tool path constraints using traditional milling methods. Normally, a cut gear will be welded to its shaft, introducing yet another potential source of distortion and reducing its structural integrity. With a ground gear this is not an issue, and again results in a better fitting and stronger component. The equipment for grinding gears is not cheap, with machines costing several millions of pounds, meaning that ground gears are usually found only in transmissions designed for very high-end applications.

The final stage of the production process will often involve surface treatment of the gears. This can sometimes involve the application of DLC or similar coatings, but many regulations ban their use on cost grounds. What is far more common is for gears to be 'superfinished' using a number of proprietary abrasive or chemical processes. Depending on the process, such finishing techniques can improve by several percentage points factors such as component durability or result in reduced friction and thus increased efficiency.

Types of differential

With the exception of specialist vehicles such as dragsters, almost all automobiles feature a differential of one type or another. The basic role of the differential is to allow the inner and outer wheels to turn at different rates as the vehicle turns, accommodating the tighter arc the inner wheel describes.

The most common type of differential is the 'open' type, which works as follows. Taking a rear-wheel-drive application, torque is supplied from the engine via the transmission to a driveshaft that runs to the final drive unit containing the differential. A spiral bevel pinion gear takes its drive from the end of the propeller shaft, and is encased in the housing of the final drive unit. This meshes with the large spiral bevel ring gear, known as the crown wheel.

The crown wheel gear is attached to the differential carrier or cage, which contains the 'sun' and 'planet' wheels or gears, which are a cluster of four opposed bevel gears in the perpendicular plane, so each bevel gear meshes with two neighbours and rotates counter to the third, which it faces and does not mesh with. The two sun wheel gears are aligned on the same axis as the crown wheel gear, and drive the axle half-shafts connected to the vehicle's driven wheels. The other two planet gears are aligned on a perpendicular axis, which changes orientation with the ring gear's rotation.

For high-performance applications, more planet gears can be used to increase the load capacity of the differential. As the differential carrier rotates, the changing axis orientation of the planet gears imparts the motion of the ring gear to the motion of the sun gears by pushing on them rather than turning against them – that is, the same teeth stay in the same mesh or contact position – but because the planet gears are not restricted from turning against each other, within that motion, the sun gears can counter-rotate relative to the ring gear and to each other under the same force (in which case the same teeth do not stay in contact).

The biggest disadvantage with an open differential is the fact that, if one wheel loses traction, all of the engine's torque will be transmitted through that wheel, with the wheel that has grip receiving none. This means that if one wheel breaks traction, for example if it is not touching the ground or is on a surface with a lower coefficient of friction than the opposite wheel, forward motion will be lost. Clearly this is less than ideal in a competition vehicle, especially a rally car where such conditions are prevalent. The solution is the use of a differential that can still accommodate a difference in wheel speed but that also allows for a degree of 'locking', thus preventing all the drive going to only one wheel. Enter the limited-slip differential, a component almost synonymous with the howl of rally cars on forest stages.

There are many different types of limited-slip differentials on the market, but they all share some basic elements. First, all have a geartrain that, like an open differential, allows the outputs to spin at different speeds while holding the average speed of the two outputs at equal to the input speed. Second, all have some sort of mechanism that applies a torque internal to the differential that resists the relative motion of the output shafts. In simple terms this means they have some mechanism that resists a speed difference between the outputs by creating a resisting torque between either the two outputs or the outputs and the differential housing.

These mechanisms can range from clutch-based systems through viscous coupling to combinations of these using electronic controls to vary the level of slip. The most common type found in competition applications relies on a clutch-based system to control the level of locking, thanks mainly to the predicable and consistent performance such a system affords.

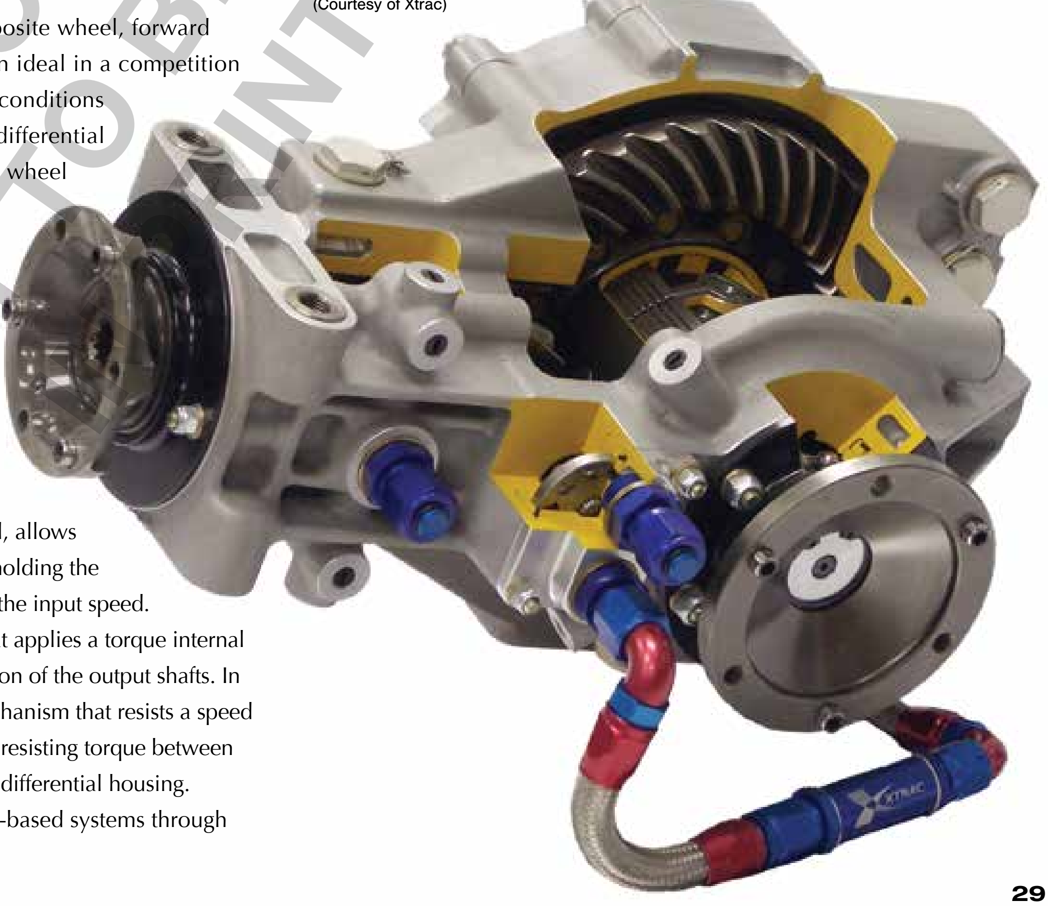
A clutch-type limited-slip differential will feature a stack of thin clutch discs, half of which are coupled to one of the driveshafts, the other half of which are coupled to the spider gear carrier. Pressure is usually introduced into the clutch pack through the use of a cammed pressure plate, which increases the force on the clutch packs as input power is increased. Different manufacturers will have their own specific designs for the actuation systems, but in general they will be adjustable for pre-load on the clutch pack springs, allowing the response of the differential to be tuned. The activation of the locking action is also normally adjustable, allowing slip to be varied depending on whether the vehicle is accelerating or decelerating, thus changing the handling characteristics of the car.

Rally requirements

The differential is one of the most important components in a modern rally car, contributing significantly to its performance potential. This impact is in terms of actual grip and, more important, the feel the differential affords the driver in order to judge available grip, allowing them to extract maximum performance from a given set-up.

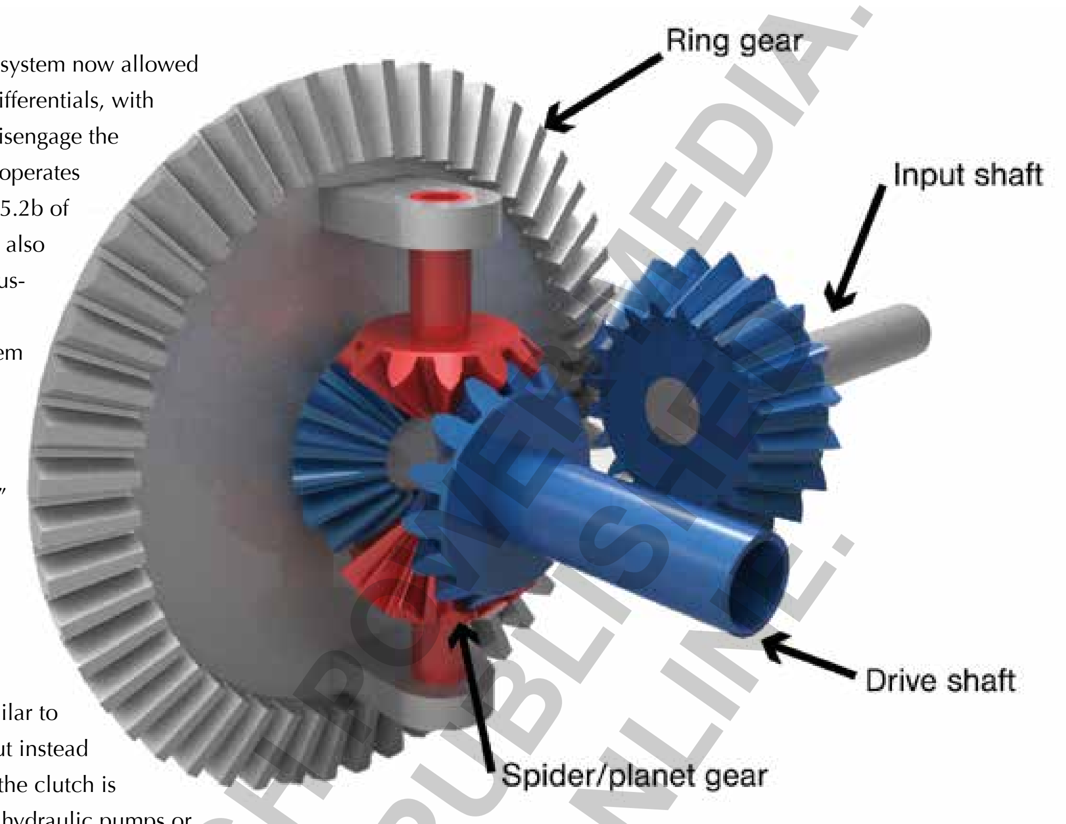
As mentioned earlier, from 2006 active front and rear differentials, which used electronic control units to vary locking characteristics, were no longer allowed in competition, and this was followed by a ▶

A cutaway showing the internals of a heavy duty rear differential. (Courtesy of Xtrac)



ban on active centre diffs in 2010. The system now allowed consists of front and rear mechanical differentials, with a manually operated centre clutch to disengage the rear propshaft (for use when the driver operates the handbrake to initiate turn-in). Rule 5.2b of the FIA regulations governing the WRC also bans the use of viscous or hybrid viscous-plate differentials, stating, "Mechanical limited-slip differential means any system which works purely mechanically, ie without the help of a hydraulic or electric system. A viscous clutch is not considered to be a mechanical system."

Despite them no longer being allowed in WRC competition, there are still many rally cars in competition globally that feature active differential technology, so an overview of it is beneficial. Active differentials look similar to clutch-type limited-slip differentials, but instead of relying on clamps or other devices, the clutch is controlled by an ECU and actuated by hydraulic pumps or electric current.



The common arrangement found in an open differential

At its most basic level, an active differential can control the level of slip in the diff using information gathered from various sensors, but those found on WRC cars were far more complex than this. Through the use of front, rear and centre diffs, linked through a main ECU, the level of wheel slip could be controlled on each corner of the car, with torque being transferred both laterally and from front to rear. Each differential would be mapped, much like an engine's ECU, and drivers would often have access to several different maps from a dashboard controller. The ECU would draw data from multiple sensors – typically those for throttle, rpm, speed, brake pedal, handbrake, switch position and so on – and interpolate the information onto a 3D map that then established the appropriate amount of differential lock for the particular driving circumstances.

Throughout a corner, drivers would be looking for the car to behave in a certain way, so the relationship between throttle position and the state of the diff was very important. For example, under braking, the diffs would initially lock fully, providing a very stable platform, but as steering angle was applied (still under braking) the locking had to be eased back to prevent understeer. Given the huge variety of surfaces experienced during a rally, this capability was evidently a great advantage, and unsurprisingly the development of differential maps was an ongoing process for engineers. Unfortunately, such open-ended technical development cost money, and with the WRC looking to reduce spending in the sport the active diff became a casualty of new regulations in 2006. Mechanical differentials are still adjustable by the drivers, but only to a limited extent. On most units the pre-load can be loosened or tightened manually between stages, but any more meaningful adjustments can only be made in the Service Park. This means that consistency of performance becomes the primary consideration, allowing the driver to have faith in the way the chassis will react, and allowing them to drive closer to the limit. Consequently, any variability is 'dialled out' of the car during set-up to enable the driver and rally team to concentrate on tyre and suspension performance.

As the differentials are passive in operation, many of the characteristics of their operation can only be altered by changing the internal hardware. It is here that regulations governing homologation changes come into play again; if the initial set-up of a new differential design is not just right, further development and tuning can be difficult within the rules. To counter this, some differential manufacturers can 'map' the performance of their differentials, using specialised test rigs. These allow them to fine-tune the torque distribution and locking characteristics of a differential to exactly match a team's requirement prior to a unit being homologated. While regulation changes over recent years have seen the banning of exotic solutions such as active diffs, the result has been a greater focus on gaining performance from passive units.

Conclusion

While no racing transmission has what could be described as an easy life, rallying provides a uniquely hostile environment that literally batters components into submission. This is evident in the developments highlighted in this article, with the manufacturers' task being made even more complex by regulations that require extended longevity from components. Despite engineers' wings being clipped by these same regulations, the new challenge is producing more performance from passive components, without the aid of complex electronic control systems.

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