Differentials Explained

In the first place, why do we need differentials at all? In the early days of the motor vehicle, designers soon tumbled to the fact that a solid rear axle wasn't the ideal arrangement across the back of a car.

When the machine went around a corner the outside wheel dictated the rotational speed and the inside wheel had no choice but to spin off excess speed. With skinny, solid rubber tyres, narrow-track axles and dirt surfaces that was tolerable, but when wider vehicles, better-gripping tyres and high-friction tar-macadam surfaces came along things had to change.

The simple solution was to split the rear axle into two halves, with a gear-set in the break. The gears allowed 'differentiation' between the speed needed by the outside wheel and the inside wheel during a turn. That's pretty much how 99 percent of today's vehicles are set up, be they front or rear wheel drive.

The limitations of the conventional differential became obvious firstly in performance cars. If the driver gave the thing a bootful one of the rear wheels would spin and the car wouldn't move. A similar effect occurred when cornering: wheel-spin on the inside wheel if the driver 'got on the gas' when exiting a corner. Many sports and racing machines retained solid rear axles to overcome this problem and at least one – Fraser-Nash – had solid-axle chain drive in the 1930s.

The 'limited slip' differential came into being to control wheel-spin in high-performance machinery. Before explaining the design of the limited slip diff (LSD) we'll have a look at the basic differential that's been with us for nigh on 100 years.

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Normal 'Open' Diff

The basic differential is a gear-set inside the crown-wheel and pinion assembly of a final drive. The bevelled crown-wheel and pinion turn propellor shaft rotation through 90 degrees.
The 'break' in the solid axle we discussed earlier is filled with gears. On the end of each axle half-shaft is a gear, known as a side gear. The two side gears are meshed together by pinion gears, so we have an assembly with two axle half shafts that are geared together, but in which one can over-speed the other.

A pinion shaft runs through the centre of the pinion gears and through the casing that's bolted to the crown-wheel, so that although the two side gears and their half shafts can vary rotational speed between themselves the whole assembly rotates with the crown-wheel.

Some differentials have four pinion gears, in which case the pinion shaft is replaced by a 'cross'.

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A conventional, ‘open’ differential works fine so long as both wheels on the axle have a good grip on the ground. Its limitation is that when one wheel loses grip all the drive goes to that wheel – wheel-spin. As well, the other wheel doesn’t move and the spinning wheel does so at twice the speed of the crown-wheel.

In an off-road situation the vehicle not only can’t move but is likely to dig a hole because of excessive wheel-spin. That’s why most 4x4s have some form of wheel-spin limitation.

Limited Slip Differential

The majority of LSDs on the market are factory-fitted and nearly all of them are based on the open differential design we’ve discussed. The difference is that LSDs have clutch packs inside their differential cases and these serve to restrict wheel-spin – hence the name ‘limited-slip’ differential.

The clutch packs fit between the side gears and the differential casing, pressurised or pre-loaded by spring plates. When one wheel starts to spin the clutch packs on that side resist the action. The spring pre-load pressure is enhanced by the ‘separation’ effect that the side gear develops when it starts to spin, but even the most powerful clutch-type LSD needs some wheel grip on both half shafts to function.

With one wheel clear of the ground a clutch-type LSD is no more effective than an open diff.

Clutch-type LSDs have been fitted as standard equipment to the rear axles of virtually all new 4x4s, except Land Rovers and Range Rovers, since the 1980s.

Enhanced-Clutch LSD

The Thornton and Dominator limited slip differentials enhance the gear-separation effect that occurs when one side gear starts to spin. In these four-pinion LSDs the pressure rings that transmit gear-separation forces to the clutch packs have V-shaped cutouts that bear against the pins of the central ‘cross’. As the side gear spins faster than its opposite number the clutches on that side resist the action and the gear-separation forces are magnified by the ramp action of the pressure rings against the cross pins as friction tries to rotate the pressure rings.

This type of LSD still needs some traction on one wheel to be effective, but the action is more powerful than that of a conventional LSD.

Locked Drive Systems markets the Dominator and one standard Thornton installation we know of is in the rear end of the Mitsubishi Canter 4x4 light truck.

A variation on the enhanced LSD theme is the Gearless Locker In this diff there are no side gears and pinions, just two pressure rings with clutch packs inside and a power dividing cross-pin. The makers Tractech Inc. claim that the Gearless Locker is the first non-geared LSD to offer complete diff-locking, so that in theory it should work when one wheel on an axle has no grip.

Cam and Plunger LSD

The BTR Hydratrak LSD was developed by BTR Engineering of Australia, but in principle is similar to the diff used for many years in Mack Trucks.

BTR diffs are used in many high-performance cars and also featured in the discontinued Falcon Outback ute. We drove an Outback over Big Red, so we can testify to the grip it provided.

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The advantage the BTR unit has over the Mack system is that the cam and plunger assembly is self-contained, with its own fluid supply, independent of the axle oil.

The BTR design uses a conventional side-gear-and-pinion centre, but one of the side gears is far from conventional. It's a multi-part assembly and on the reverse side of the input bevel gear face is a 'wave' machined pattern. The output half of the side gear that's splined to the axle half-shaft has a similar wave pattern machined on its inner surface.

Between the two wave faces is a hub, with plungers that are free to move back and forth inside the hub. At their outer ends these plungers bear on the wave surfaces of the two-part side gear.

Under straight-driving conditions the input and output halves of the side gear have no relative movement and the drive is passed from one wave face to the other via plunger contact.

When the vehicle corners the required differential action takes place in the diff centre, but if one wheel starts to spin the wave faces start to move relative to each other. The plungers won't tolerate too much relative movement of the faces and lock in position, restricting wheel-spin.

Gear-Type LSD

The Torsen and the Detroit TrueTrac are the best-known gear-type LSDs in the 4x4 world. The Torsen was available as an option in the rear end of the initial RAV4 and is the central differential some Range Rovers. The TrueTrac is a popular after-market fitment.

In gear-type LSDs the side gears are helical-cut cylindrical gears and so are the pinions. Instead of being enclosed within the side-gear diameter the pinions in a gear-type LSD sit outside the side gears and are pinned to the differential casing.

Although there are design differences between the Torsen and the TrueTrac, both have pinions that mesh with each other and with the side gears in a pattern that allows differential action under normal driving circumstances.

When one side gear starts to spin the helical nature of the gearing imparts an angle to the separation forces between the side gears and the pinions, forcing the ends of the pinions into friction contact with the diff casing. The action limits wheel-spin and apportions torque proportionately.

Viscous-Coupled LSD

Viscous coupling units (VCUs) have been with us for many years, initially in the hubs of engine fans. The heart of a viscous coupling is a silicon fluid that thickens when it gets hot. Put that stuff inside a housing full of friction plates that are splined alternately to the housing and the output shaft and you have a coupling that has an output dependent on temperature. In the case of an engine fan, air flowing from the radiator across the fan hub speeds up or slows down fan action.

In a 4x4 diff a viscous coupling has the same potential. Splined between a side gear and its half shaft a VCU can limit wheel-spin, by restricting relative movement.

At one stage it was thought that VCUs would replace conventional diff centres, with differential action and slip-limiting occurring entirely inside the VCU, but real-world experience has poured cold water on the idea, to date at least.

The problem is that VCUs react to heat, regardless of its source. The unit can't differentiate between heat generated internally by wheel-spin and heat produced by friction and radiation in the axle of a 4x4 operating at low speed in high ambient temperatures.

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Conversely, a VCU doesn't respond instantly to wheel-spin if it's in a vehicle that's been parked all night in a snowdrift, because it can't heat up quickly enough. That isn't a problem for the VCU in the engine fan, because it isn't needed at start-up, but the diff VCU may well be needed to help extract the vehicle.

The variable-behaviour nature of VCUs is why most 4x4s that have VCUs in their transfer cases have a positive diff lock-up in low range.

Hybrid LSD

The original Mitsubishi Challenger used a hybrid LSD that combined a gear-type LSD and a VCU.

The gear-type centre section looks very like a Tractech TrueTrac, with four short pinions and four long ones. This type of diff centre lends itself to coupling with a VCU, because the pinions are located outside the side gears, leaving a hole in the middle of the diff centre.

In the case of the Challenger's hybrid diff the hole in the centre is filled by an extension of the VCU hub, mating it to the right hand side gear. The left hand side gear is integral with the housing of the VCU.

Under normal conditions the VCU plays no part in proceedings and the side gears and pinions do their thing. Even at the onset of wheel-spin on one side of the vehicle the diff functions as a gear-type unit.

When one wheel has no grip the VCU comes into play. The meshing forces in the gears generate little friction with one wheel in the air and so that wheel and side gear start to spin. The relative movement between the left and right side gears generates heat in the VCU, which then provides the necessary drag for the gear-type LSD to function properly.

Self-Lockers

The best-known self-locking differential is the NoSPIN that's been around in much the same form for the past 50 years. Another design is the Lock Right.

Although called self-lockers these diffs would be better described as self-unlockers, because they're locked unless differential action is required.

In a NoSPIN the differential case and its side and pinion gears are replaced by a spider, clutch and side gear assembly. The central spider has dog-clutch teeth on both faces that match dog-clutch faces on a pair of sliding clutches that are in turn splined to a pair of side gears. Sandwiched between the side gears and the clutches are tapered-spiral coil springs.

Cam faces are machined on the inner diameter sections of the spider and the clutches. These cams push one clutch away from the spider when differential action is required, allowing that half shaft to over-speed the other. In older NoSPIN designs this cam-out phase was accompanied by a ratchetting noise, but later designs have cam ramps that allow a smooth cam-out phase.

When differential action is no longer required the spring pushes the dog clutch back into mesh with the spider.

Unlike LSDs self-lockers don't rely on any torque transfer across the differential – they deliver 50 percent torque to each wheel, regardless of the grip, and will drive a vehicle that has one wheel with grip and one in the air.

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Hydraulic Lockers

Jeep's Grand Cherokee Quadra-Trac II transfer case and axles used to be fitted with a Vari-Lok patented hydraulic diff-locking system. The principle is simple: wheel-spin energy is used to drive a pump that pressurises oil in a wet clutch pack. The pack inside the transfer case prevents front or rear axle spin-out and the pack in each axle prevents wheel-spin on one side.

In the Quadra-Trac transfer case the oil pressure comes from a gerotor pump that's integral to the transfer case shafts and in the axles the pump is in the centre of the diff, where it's fed oil by slingers.

Interestingly Jeep abandoned the viscous couplings it used in the original Grand Cherokee in favour of the pump system, citing variable response in VCUs as the reason. The latest Jeeps use electronic traction control.

Driver-Controlled Diff Locks

All 4x4s that have full-time 4x4 or selectable full-time, part-time 4x4 drivelines and low range transfer cases have driver-controlled diff locks. The control is done by a switch, or by engaging low range.

(The exception was the first traction-control-equipped Land Rover Discovery, but the 'missing' diff lock was there – you just couldn't switch it on or off without mechanical interference in the top of the transfer case. Land Rover re-instated driver control of the central diff lock with the next model.)

This type of diff lock is positioned in the transfer case and is there to force the front and rear propeller shafts to rotate at synchronous speed. It does nothing for traction improvement, other than to prevent spin-out at the front end of a vehicle climbing a steep grade. With its centre diff locked a full-time 4x4 has no basic traction advantage over a part-time 4x4.

Diff locks that impart distinct traction advantage are fitted to the axles and lock the half shafts into 50:50 torque proportion, regardless of the grip each wheel has.

The best-known across-axle diff lock brands in the Australian market are ARB, TJM and Toyota. These designs lock out differential action, but do so with different mechanisms.

In its diff-locked rear axle Toyota uses a sliding collar that locks the right-hand half shaft to the differential hemisphere. In the front axle a sliding collar locks the right hand side gear to the differential casing.

When Toyota introduced its optional, factory-fitted diff lock system to the 60-Series and the 75-Series it was cable actuated, but by the time the 80-Series arrived the actuation method had switched to electric motors.

ARB's Air Locker has an internally-toothed hemisphere, an externally-toothed side gear and a locking gear that slides between them. The actuation method is compressed air.

The specialist diff lock system for Land Rovers and Range Rovers is the Maxidrive.

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