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Differential

When a car negotiates a turn, the outside drive wheel travels a longer distance (rotating faster) than the inside drive wheel (rotating slower.) If the drive wheels are tied together they can't rotate at different speeds which makes it particular difficult to execute the turn as the you get a combination of the outside wheel dragging and the inside wheel spinning. Ultimately this results in damage to the tires and difficult handling. In simplest terms, a differential allows the inside and outside wheels to rotate at different speeds while still being able to apply power.

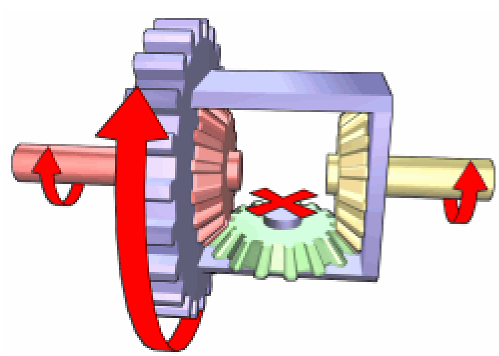
There are a number of different basic differential designs. They broadly fit into the three categories of "Spool", "Open" and "Limited Slip". Of the limited slip type, there are a number of different designs. This article will focus only on the "Clutch Type Limited Slip" and "Torque Biasing" designs which are also known as "Torque Sensitive" and will not discuss "Lockers", "Viscous Coupling" or other electromechanical, pneumatic or hydraulic types of limited slip differentials which are known as "Speed Sensitive".

Spool

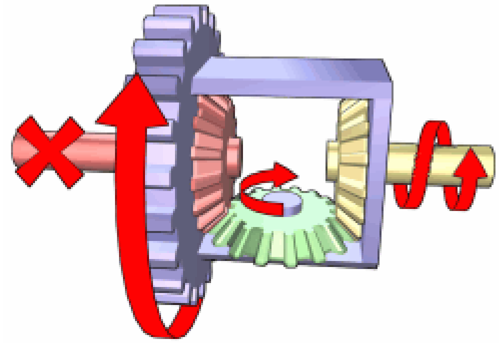
A "Spool" is actually not a differential as by design it does not allow the two drive wheels to turn at different speeds. It purpose is to ensure that both drive wheels turn at the same speed. It is used in some race cars and is more commonly found in drag and drift racing. An inexpensive way to create a spool is to weld the spider gears of a traditional open differential. This prevents the open differential from working as intended.

Open

A traditional "Open" differential is the most common type found in cars today. It is a relatively simple mechanical design that typically consists of a set of four beveled gears that live within the differential carrier. Half shaft axles are connected to these for power delivery to the wheels.



Open Differential. Both wheels traveling at same speed.



Open Differential. One wheel locked.

What may take many words to explain has been well explained in a 1930's General Motors short film. As they say a picture is worth a thousand words...

Link to YouTube video of how a differential works

The primary problem with a traditional open differential is that if a single wheel spins freely such as in ice conditions, or by the application of too much drive power, all of the power will be transmitted to the wheel that is spinning (path of least resistance). The other wheel which may have effective traction will get little or no power. This is a particular problem on high performance and race cars which have the ability to break traction at will.

Limited Slip

The goal of a Limited Slip Differential (LSD) is to allow some rotational difference of the two output shafts, but at the same time to limit the rotational difference. In some situations, high performance vehicles benefit from having a LSD. For example when applying power while exiting a turn, a car with a traditional open differential may spin one of the two tires slowing overall acceleration. When using a LSD, this unintended wheel-spin may be reduced or even stopped allowing the car to exit the corner faster. LSDs can also help under braking as well.

1, 1.5 AND 2 WAY

A torque sensitive limited slip generally operates in one of three states. "Load" (acceleration), "No load" (coasting) or "Over Run" (deceleration/braking). Limited slip differentials are commonly classified as "1 Way", "1.5 Way" and "2 Way". "1 Way" provides locking during load only. During over run it acts as an open differential. "2 Way" provides identical locking during both load and over run. "1.5 Way" works like "2 Way", but with a reduced locking on over run. "1 Way" are also considered the "safer" type as when the driver lifts off the throttle or brakes, without any locking on over run, the car feels like it has an open differential. “1.5 Way” can be considered to be a compromise between a “1 Way” and “2 Way”.

TORQUE BIASING

Torque Biasing differentials (TBD) utilize worm and other special gears instead of clutches. These work by sensing a torque imbalance between the two wheels. If one wheel begins to move faster than the other, the TBD attempts to move torque from the faster to the slower wheel. This transfer occurs due to purposeful binding of the gears within the TBD. The design of the gears provides a multiplying factor known as the torque bias ratio. This may be something such as 5 to 1. This means that a TBD with a ratio of 5:1 can provide five times as much torque to the wheel with traction than to the one with limited traction. However this also means that the amount of torque applied is based upon the amount of torque available to the slipping wheel. If the slipping wheel has zero or nearly zero traction (such as in ice conditions or if the wheel is off the ground), then little or no torque is applied to the wheel that does have traction. Five times zero is zero. Because of this, TBDs are technically not limited slip, but rather torque multipliers.

So in some conditions a TBD can operate nearly identically to an open differential. TBDs also act as 1 Way LSDs only. So they are populate in front wheel drive application. While TBDs have limitations, they also have benefits.

A TBD generally costs substantially less than a clutch type LSD. As they are geared devices, they do have the benefit of being generally maintenance free, especially when compared to clutch type LSDs which experience wear to the clutch plates over time. Torsen is a commonly recognized manufacture of TBDs. Guard Transmission and Quaife provide TBDs for a wide range of Porsches including those used in early 911 and 914s.

CLUTCH TYPE LIMITED SLIP

Clutch Type LSDs are constructed similarly to that of a regular open differential, however they include a series of discs (the clutch pack) that are used to limit the amount of rotational difference. The clutch disks come in two types. The first is called the “outside disks” and are splined so that they mate to the the outside of the disk (inside of the differential carrier the slide inside). The second are called the “inside disks” and are splined so that they mate on the inside of the disk (outside of the hub they slide on). One type of disk has a friction material and the other does not.

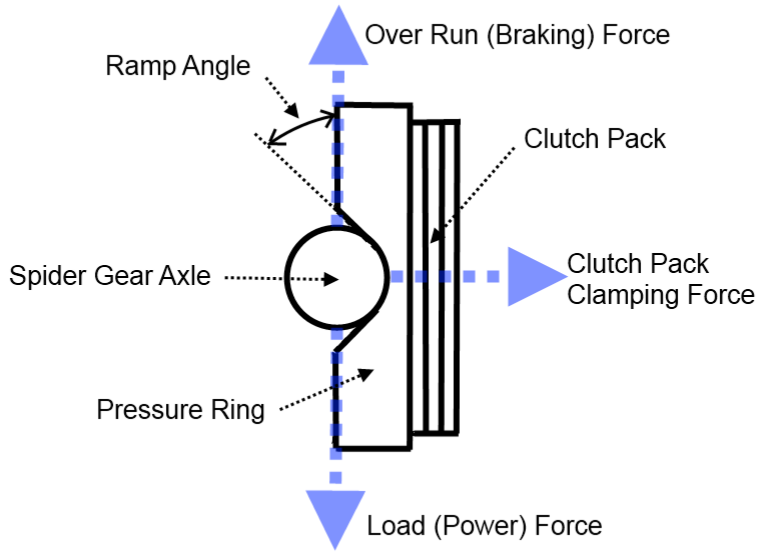
Clutch type LSDs, are produced by a number of manufactures. In general this design provides for the ultimate in configurability as there are a number of things that can be changed that affect their operation, but generally at a higher overall cost and increased long term maintenance costs (clutch disks for example wear over time)

Ramp Angles

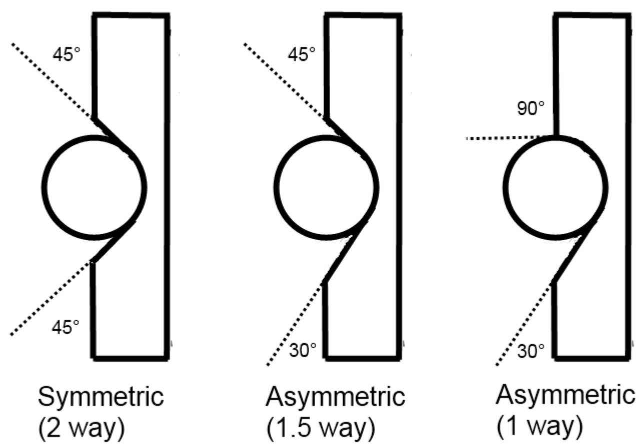
Within the clutch type LSD, there must be a method to apply pressure to the clutch pack in dynamic conditions (load or over run). This is generally accomplished by what is known as a thrust or pressure ring (depending upon the design of the differential there may be one or two pressure rings) which applies pressure to the disks within the clutch pack. On the pressure ring are ramps that work in conjunction with the axle of the internal spider gears. In either the load or over run conditions, the spider gear axle tries to ride up the ramp. As the spider gear axle does not move, the force from the axle transfers force via the pressure ring to the clutch pack. A ramp with a shallow “ramp angle” results in more pressure being transferred to the clutch pack. A steep ramp angle results in less (or no) pressure being transferred to the clutch pack. Additionally there are opposing ramps with one for for load and the other for over run conditions

If the load and over run ramp angles are identical (symmetrical) then this can be considered a “2 Way” configuration as the amount of load placed on the clutch pack is the same for both load and over run. If the over run ramp is effectively a steep wall, then there is no additional pressure transferred to the clutch pack on over run. This is a “1 Way” configuration. If the load and over run ramps have different angles (asymmetric) then the pressure transferred to the clutch pack is different for load and over run conditions. This is a “1.5 Way” configuration.

Ramp angles are usually denoted as load first and over run second. So a 40/60 would be an asymmetric 1.5 way with a shallow ramp angle for load and a steeper ramp angle for over run. Any combination of ramp angles may be used and are a major determining factor in the locking effect. The actual ramp angle is only limited by the creativity of the LSD designer.



Clutch Type LSD. How load and over run forces are transferred to the clutch pack as a clamping force.



Clutch Type LSD. Symmetric and Asymmetric ramps.

Preload

In addition to ramps which increase the dynamic clamping force on the clutch pack load or overrun, an amount of static preloaded pressure can be placed on the clutch pack to increase the amount of friction (and locking force) generated by the clutch pack. This preload can be zero or a larger value. The preload is usually set by spring washers (such as a belleville washer), stacking washers, or optimal selection of clutch disk thicknesses. While this preload impacts not just the amount of lock in no load, but also load and over run conditions. Preload is a large contributor (along with clutch pack configuration, clutch material, etc.) in what is known as "break away torque". This is the rotational force required to rotate one axle while the other is held firm.

Clutch Pack Configuration

As the clutch pack is made up of a series of disks that mate to either the outside (differential housing) or inside (output shaft) you would expect them to be ordered using an I, O, I, O alternating order. And they may be ordered that way. Or, you may choose to order them differently such as O, O, I, I. Friction disk material and thickness are other variables that can be adjusted. All of this is done to increase or decrease the amount of friction and ultimately the amount of anti-slip.

Percent Locking/Anti Slip Effectiveness

Early LSDs (such as the Porsche ZF units) would not list the ramp angle in their specification. Rather they would use a percentage value to indicate the “percentage of anti slip”. So a “40% LSD” would have more slip than an “80% LSD”. Higher numbers equates to lower slip levels (or higher locking). This nomenclature was easier to use especially in early differentials that were symmetric 2 way designs.

Early Porsche ZF LSDs used 30 degree symmetric ramps. By varying the number of friction disks in the clutch pack, you could either create a 40% (2 friction disks), or a 80% (4 friction disks). Later Porsche LSDs used asymmetric designs, but they still used percentage values instead of ramp angles. In general a shallow ramp angle (smaller angle value) will result in a larger locking percentage and visa versa. So for example a 30 degree ramp may result in 80% locking and a 90 degree ramp may result in 0 % locking.

Most LSD manufactures list percent locking/anti-slip values instead of ramp angles as ramp angle is just part of the equation that defines the level of anti-slip. Be careful to not confusion percentage values with ramp angle values.

How does all of this fit together?

It can be very confusing as there are a lot of different factors that impact the static and dynamic behaviour of a clutch type LSD. Given a single basic LSD design, the following items impact LSD performance...

- Ramp angle (both for load and over run)
- Preload
- Clutch pack configuration (number and orientation of friction disks)
- Friction disk material
- Lubrication (level and type of friction modifier additives that are in the oil)

All of these come together to define how the LSD behaves in various situations. Ramp angles and preload set the amount of static and dynamic force applied to the clutch pack. Clutch disk material, orientation, count and lubricating fluid all then factor into the final level of friction available. Combining this force and friction levels and you generate a level of anti slip effectiveness that can range from nearly zero to enough to lock the differential at all times.

This should indicate that it is also very difficult to compare one LSD to another based upon a few simple parameters. Two differentials with identical ramp angles may operate totally differently due to differing preload, clutch disk orientation, etc.!

You can also create wildly differing combinations. For example you might have a high preload with relatively steep ramp angles. This will means that the amount of locking starts high, but doesn’t change that much in load or over run condition. Or you might have low preload with shallower assymetric ramps. This will mean that the amount of locking start low, but rises faster in load conditions and less faster in over run conditions.

How do I decide what I should use?

There is no single best solution. It very much depends upon things such as...

- Application (street car, autocross, dedicated racing, etc.)
- Budget

Maintenance expectations

If you are building a road race car, want infinite adjustablility and have the budget, then some type of clutch based LSD is the way to go. Some types of racing likes a spool differential. If you are on a tight budget you should consider a TBD. There are many who feel that TBD works well for autocrossing as well as street driven cars. Clutch style LSD wear out eventually while TBDs may have effictively zero maintaince other than observing a regular lubrication maintenance schedule. In short, you probably will need to work with your mechanic and maybe even a differential supplier to help determine what fits your specific needs. Some suppliers may offer multiple styles of differentials and they should be able to help you decide what is best for you.

Last Revised: 8/26/2012