

# **DIFFERENTIALS AND CHASSIS SETUP**

By Craig Taylor

The purpose of this article is to identify the common types of differentials in common use today, to define their operation, and to discuss the setup implications of the various differentials. In order of discussion: Open Differential, Spool, Detroit Locker, Cam and Pawl, Salisbury (Hewland Powerflow) and Automatic Torque Biasing differentials. The viscous and hydraulic pump differentials will also be briefly discussed. Computer controlled differentials will not be discussed.

The only reason that a differential is needed in any car is to allow the outside wheel to roll through the corner at a higher rate of speed than the inside wheel. The term differential refers to this difference in wheel speed when cornering. If we only went straight, no differential would ever be needed.

## **OPEN DIFFERENTIAL**

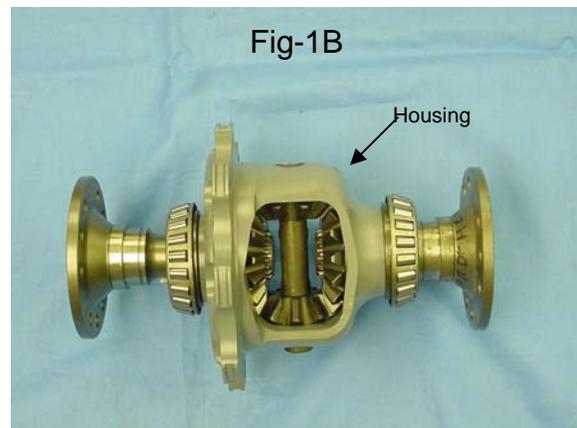
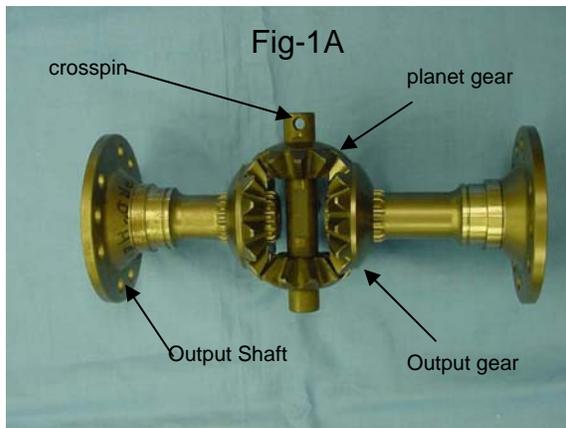


Illustration 1A and 1B show the common open differential. The driving torque, taken from the ring gear passes through the differential housing to a crosspin, which passes the torque to the spider (or planet) gears, thence to the output, or side gear. The open differential always splits the torque 50% to each wheel. The even torque split gives the most predictable handling and is easiest to set up, tunable with just springs, swaybars and dampers and caster. Handling is consistent through a wide range of power application.

The limitation of the open differential is that the thrust available is limited to the maximum thrust (acceleration grip) of the wheel with the poorest grip. Again, with a 50-50 split of torque, both tires have exactly the same thrust, limited by the tire with weaker grip.

With low powered cars running slicks (Formula Ford, F2000, and on fast tracks Formula Atlantic), the open differential is the best choice. These cars simply do

not have enough power relative to their grip to cause wheel spin if the chassis properly set up. A number of years ago, famed race car designer David Bruns explained to this writer that “springs put the power down, anti roll bars tend to lift the inside wheel.” Therefore if wheel spin is a problem with low powered cars, increase rear spring rate, and reduce swaybar stiffness at the rear. This will keep the roll couple the same, yet the springs will plant the weaker tire. Additionally, caster tends to unweight the outside front and inside rear when the front wheels are turned. Therefore a reduction in caster will help inside rear grip.

## SPOOL

Fig-2



Illustration 2 shows a spool (*photo provided by Mark Williams Enterprises*). The spool simply ties the two wheels together eliminating all differential action. The housing itself is internally splined to receive the drive axles. The driving torque, taken from the ring gear drives the axles directly. Both wheels turn at the same speed regardless of traction levels, or direction of travel. This means that when equipped with a spool, the car naturally wants to go straight, regardless of steering input. Again, the primary chassis handling

tools available are springs, sway bars, dampers, and caster.

Although power can be applied up the limit of the combined traction of the rear wheels, handling suffers greatly when using a spool, because the tied-together rear wheels cause massive understeer. Understeer can be reduced to some degree by reducing spring rates, and increasing sway bar stiffness at the rear. This will “unplant” the inside rear, as the sway bar will tend to lift the inside rear. Also, if the driver is strong enough, increasing caster will help to unweight the inside rear wheel during turns.

Another very significant downside to the spool is that when you are leaving the track with hot tires, the torque generated in turns can easily be enough to break axles. Remember that on the track, the inside wheel is unweighted, reducing its traction; so that the torque required to force the inside wheel to slip in the turns is reduced. When leaving the track, the weight is equal on both hot tires, the maximum grip possible on both tires will be achieved with the inside tire fighting the outside tire. Many Sprite and MG Midget drive axles have been broken because of the spool. The basic rule of road racing with a spool is DON'T. The spool is only slightly better than a ratcheting differential such as a Detroit locker.

## DETROIT LOCKER DIFFERENTIAL

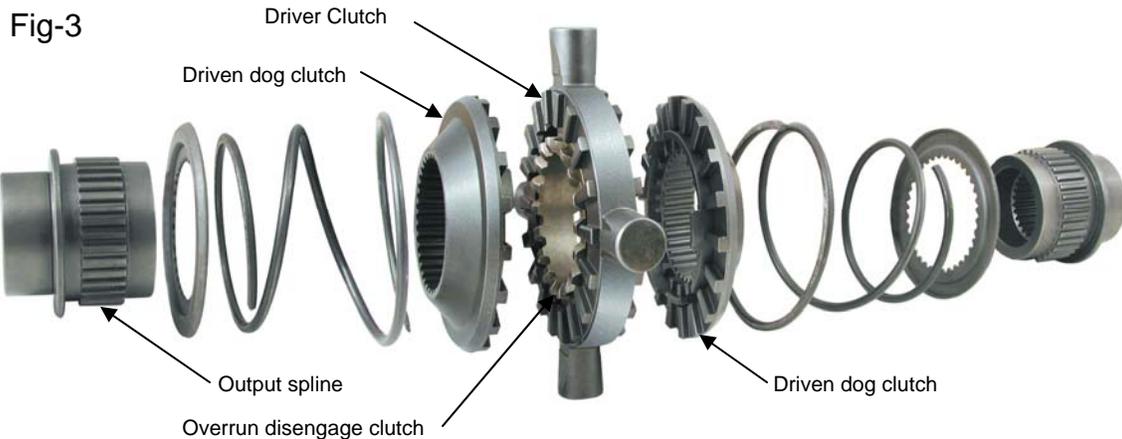


Illustration 3 shows a Detroit Locker (*photo provided by Eaton/Detroit*). The operating principal of the Detroit Locker is much like that of a bicycle rear wheel sprocket. It was originally built for drag racing to allow the turnoff at the end of a run with less stress induced in the axles. When turning off, the faster wheel will unlock allowing it to coast through the corner. This is a great setup for drag racing and off-road use. However, in a road racing application only the inside wheel will drive creating massive mid turn understeer. Only when the inside tire slips and catches up with the outside tire will the outside tire begin to drive.

At this point, the Detroit Locker becomes a spool, and the same tuning tips apply. Increasing sway bar stiffness and reducing spring rate will help lift the inside tire, reducing grip. Increasing castor will also assist, again if the driver is strong enough.

The only advantage of the Detroit Locker over the spool is that turn-in is improved over the spool. In mid turn it is worse than a spool, because the inside wheel only provides thrust as power is added after turn in. Only when enough power is added to cause the inside tire to slip and catch up to the outside wheel do both wheels drive. It is at this point a spool. This is the reason that the driving technique with a Detroit Locker is basically “pitch and power” – rotate the car into the corner using brakes to get the turn started, then slam on the power to break the inside tire loose so it can catch up to the outside, then using power to keep the car rotating through the corner. This is not the smoothest or fastest way around a corner.

Setup for a Detroit locker is the same as a spool. Relatively softer springs and stiffer sway bar at the rear of the car and more caster.

The basic rule of road racing with a Detroit Locker is the same as a spool. **DO NOT USE IT** unless it is required by the rules (Trans Am).

## CAM AND PAWL DIFFERENTIAL

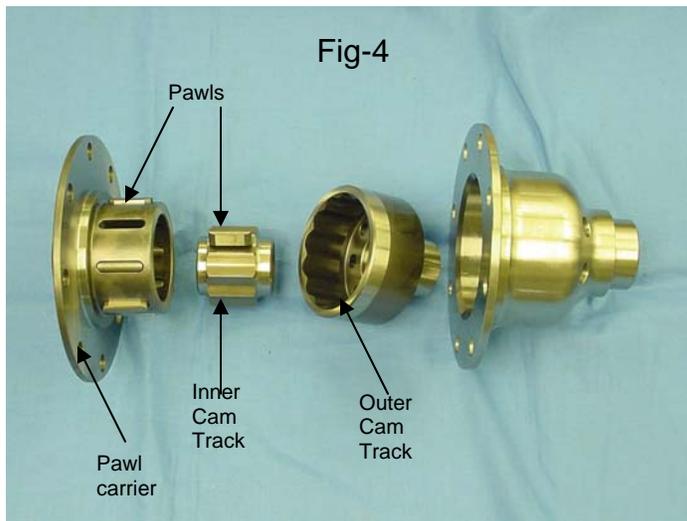


Figure 4 shows a cam and pawl differential. It is one of the earliest “limited slip” differentials used in road racing and can be seen in many F1, Formula Atlantic and 2-Liter sports racers up to the late 1970’s. As with the Detroit Locker, the Cam and Pawl is a locking differential. The difference is that the diff locks with applied torque, driving both wheels as a spool. The path taken by the power is from the ring gear to

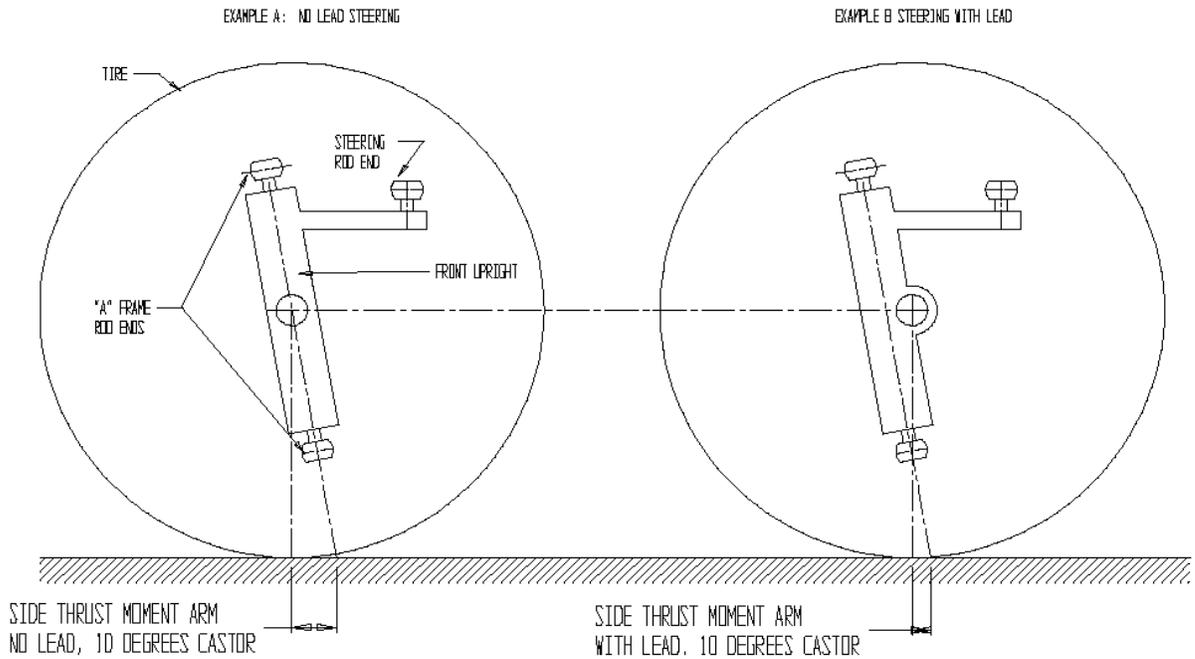
the pawls (Chiclets) via the differential pawl carrier which pushes on the side face of the pawl. The pawls are forced into the notches in the inner cam track and outer cam track causing the differential to lock. The advantage of the cam and pawl over a spool or Detroit Locker is that the lockup is predictable, occurring whenever power is applied. It also has the better turn in performance of a Detroit Locker. Mid turn power on push is again a problem because the cam and pawl locks into a spool when power is applied.

The setup for the Cam and Pawl differential is similar to the Spool and Detroit Locker: Softer springs, stiffer sway bar, and increase in caster. Formula Atlantic, F1, and 2L sports racers run with a Cam and Pawl typically have a very large (1” or greater) sway bar with short, stiff blade adjusters used to lift the inside tire on cornering. In setting up the car the weaker tire must remain on the ground to apply enough torque for locking. If the tire lifts free of the ground it will spin freely, with no forward thrust on the “good” tire.

There are some race engineers with exceptional drivers that still run the Cam and Pawl for street racing. The square turns, and drag race straights are well suited to the “pitch and power” style of driving.

The Cam and Pawl differentials should be removed and inspected after each race weekend, as they tend to wear quickly especially in higher powered cars. The pawls (Chiclets) should be replaced when the cylindrical edges of the pawls become roof shaped. The inner and outer cam tracks should be changed when the peaks are worn down more than .010”. The cam and pawl differential is expensive to maintain properly as the replacement pawls, inner cam track and outer cam tracks are very expensive.

Fig- 5



Extreme caster has been mentioned above several times. Normal caster for a Formula and sports racer is between 3 and 5 degrees. Above 5 degrees the steering effort of heavier cars can exceed the driver's endurance. This is caused by tire contact patch moving progressively farther behind the steering axis as caster is increased. Therefore, when designing for a Spool, Detroit Locker or Cam and Pawl, the engineer will frequently design "lead" into the front uprights. Lead is achieved by placing the wheel spindle slightly ahead of the steering axis, thus bringing the contact patch closer to the steering axis, reducing steering load, but still allowing the weight jacking effect of caster. See figure 5.

## **SALISBURY OR CLUTCH PACK DIFFERENTIAL**

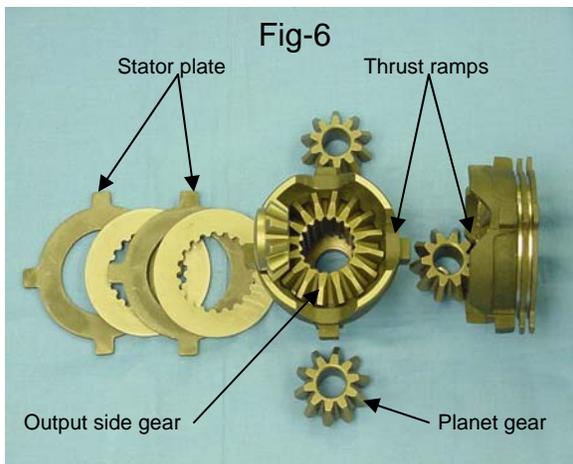
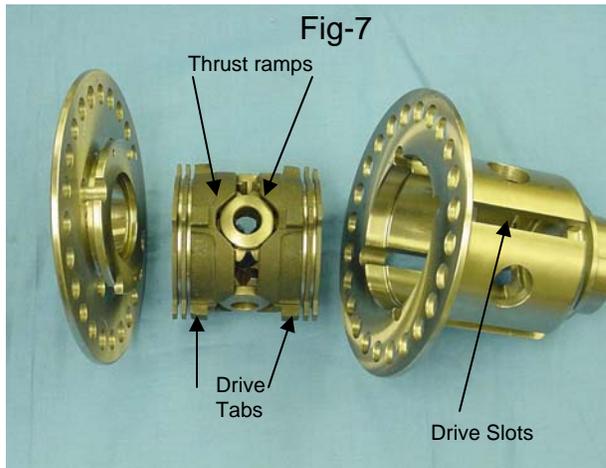


Figure 6 shows an exploded view of a clutch-pack type of differential. Common names for the clutch pack differential are Salisbury, Powerflow™ (Hewland), Torque-Lock™ (Viper), VariLock™ and others. The clutch pack differential is a massive improvement over the spool, Detroit Locker, and Cam and Pawl, in that it locks progressively with increased torque applied by the engine. This can dramatically reduce the mid turn push when the differential is set up correctly.



The clutch-pack differential is more complex than those discussed to this point. The unit consists of a slotted housing with ring gear flange, externally tabbed thrust ramps, spider gears, internally splined clutch, externally tabbed stator plates and side gears. Figure 6 shows the thrust ramps, spider gears and externally splined side gears as an assembly.

The path taken by the torque applied to the differential is complex as well. From the ring gear, the housing passes the torque to the tabbed thrust ramps, then through the planet gears, and on to the output side gears. At the same time, the force applied to the spider gears by the ramps forces the ramps outwards, compressing the clutch and stator package. (The thrust ramps can be clearly seen in figure 7.) Since the stators are tabbed to the housing, and the clutch plates are splined to the output (side) gear, when they are compressed together a portion of the total torque is passed through the clutch plates.

The proportion of torque passed by the stator and clutch plates and locking effect of the differential is a function of:

1. Ramp angles: Shallower ramps cause more compression, and more lock-up. Steeper ramps provide less clamping force, and less lock-up. A  $90^\circ$  ramp has virtually no lockup, and a  $30^\circ$  ramp can cause total lockup of the differential, making it effectively a spool.
2. Number of active clutch plate/stator plate faces: The more active faces, the more lock-up. The minimum number of active surfaces per side is 2, and the maximum number per side is typically 6. Four active surfaces have two times the lockup of two active surfaces. Figure 7 shows the clutches and stators stacked for four active surfaces per side.
3. Preload: The clutch/stator stacks can be preloaded by shimming or by the installation of a very strong Bellevue washer. Preload is measured with a torque wrench, and is the torque required to rotate the gears in the differential. (The Bellevue washer provides a more stable lockup during the course of a race weekend. They are only found on Salisbury differentials, and not on Powerflow.)

This shows that the clutch pack differential introduces a large number of variables into the chassis setup. The differential can be set up to nearly mimic an open diff, or in the extreme, a spool, and virtually any combination in between.

In general, lower powered cars with lots of tire (Formula Atlantic and 2Liter Sports racers) will use steeper ramps and fewer active clutch/stator interfaces. Additionally, very little preload is used. As a starting point, Formula Atlantic cars will be frequently set up with 80° ramps for both drive and coast, 2 active surfaces per side, and just 10-15 lb-ft of preload. A Can Am car differential could be set up with 45° ramps on both drive and coast, with 6 active surfaces per side, and 140 – 160 lb-ft of preload. The Formula Atlantic will have a chassis setup similar to that used by the open diff: Relatively stiffer springs and lighter bar at the rear. The Can Am car will be set up in a similar manner to the cam and pawl: relatively softer springs and a large rear swaybar to help lift the inside tire. The big bore car has the advantage of being able to “steer” with throttle, adding throttle to eliminate differential induced understeer on turn exit. (One trick used for Formula Atlantic cars with very steep ramps - 80° - is to place a thrust bearing at the outboard end of the side gears. This eliminates the compression caused by the spreading forces generated by the differential gears themselves, so that only the ramp-generated compression forces are applied, nearly mimicking an open differential.)

The Clutch Pack differential gives the engineer a very wide range of choices. However, the downside is that each differential change must be followed by spring, swaybar, damper or caster changes to optimize the handling. Also, the clutch pack differential is not stable in that the preload torque changes as the clutch/stator packs wear. The clutch Pack differential should be removed after each race weekend to reset the preload, and to check the clutch packs for wear. If this is not done, continuous handling changes will occur tending towards oversteer. The Clutch Pack differential also generates heat because of the slippage of the clutches as the car rounds a corner. Frequently additional cooling of the lubricant is required. Finally, if the suspension unweights the inside wheel excessively, wheel spin will result as in an open differential.

The Clutch Pack differential is a very useful tool for a professional team with good engineering expertise. It is expensive to maintain properly.

## AUTOMATIC TORQUE BIASING DIFFERENTIAL

Fig-8

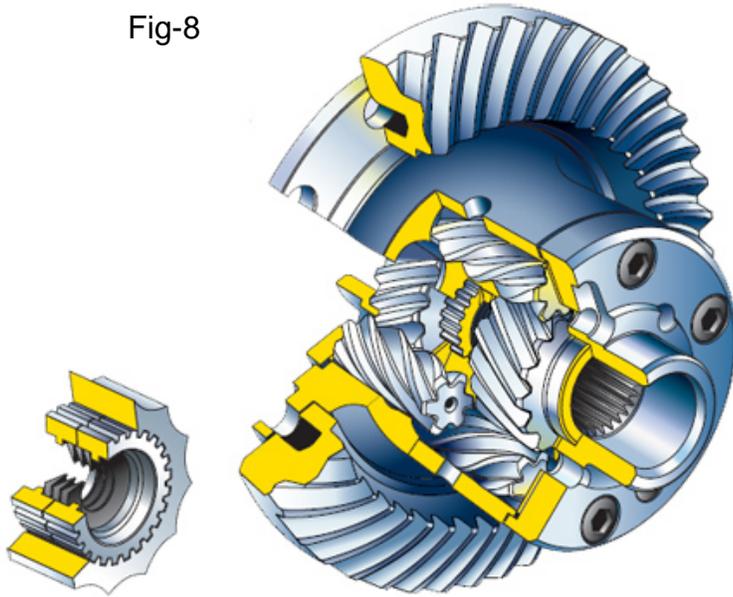


Figure 8 is a cutaway of a Quaife™ Automatic Torque Biasing differential (*photo provided by RT Quaife Engineering*). .

Fig-9

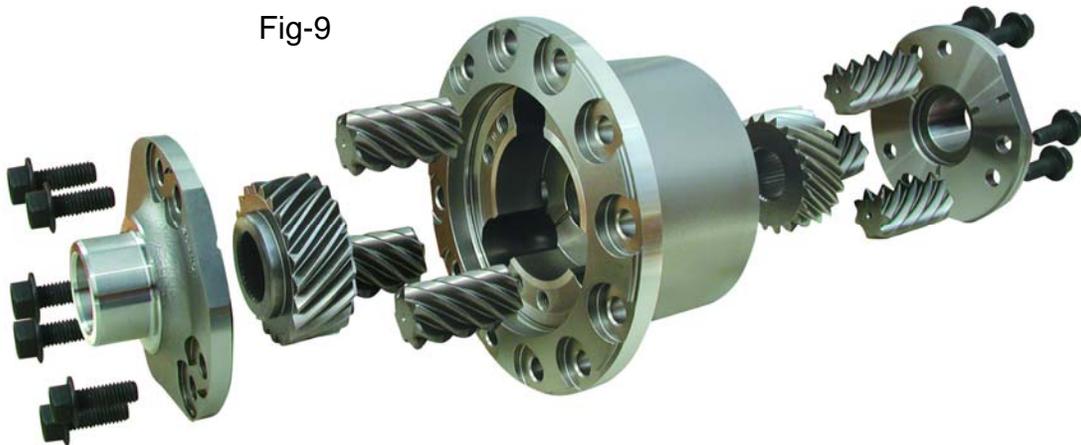


Figure 9 is an exploded drawing of an Eaton Truetrac™ differential which operates in the same manner (*photo provided by Eaton/Detroit*). The ATB differential has high helix angle side and planet gears. The three, five, or six pairs of floating planet gears provide the differentiating capability in a manner similar to the open differential. It splits the torque between the wheels equally,

50% to each if the torque applied does not exceed the grip level of the “weaker” tire. Additionally, in the Quaife unit there is a very small spring loaded clutch (inset in drawing) that exerts outward pressure on the side gears to absorb slop. This prevents the diff from being “jerky” in sudden off-on power applications.

In operation the flow of power is from the ring gear to the differential housing. The housing then transmits the torque to the planet gears in their cylindrical housings, driving them through the flattened tips of the helical gears. The torque then is passed to the side gears and to the axles. When the torque is being split equally, the end thrusts of the helical planet gears are balanced exactly by the opposing end thrust of the output side gears. This allows the planet gears to float freely in their cylindrical chambers. When one wheel has better traction than the other, and that wheel begins to slip, the end thrusts of the helical gears become unbalanced, and the steep helix angle causes the planet gears to be forced towards the end of their cylindrical chamber. This causes a slight wedging action, biasing a greater proportion of the torque to the wheel with better grip. The biasing is proportionate and linear varying between a 50% - 50% torque split to a maximum torque split of 20% - 80%.

It is important to note that, as with the Cam and Pawl and Clutch Pack differentials, the inside wheel must remain in contact with the ground, and have at least 20% of the rear weight on the inside wheel in order to have maximum torque biasing and maximum thrust of both tires. Less than 20% weight on the inside tire means less thrust capability. For example if the weight transfer nets only 10% of the weight on the inside wheel, it reduces the maximum thrust to just ½ of the total obtainable if the chassis were set up correctly. (Note: the Torque Biasing differential will continue to bias at the 80% rate, but since only 10% thrust will be available on the weak wheel, the better wheel will still have 4 times the thrust of the inside wheel, or 40% of potential.  $10\% + 40\% = 50\%$  or half the possible thrust.)

The basic setup of the car is the same as with an open differential. Relatively stiffer springs and softer swaybars, and small caster angles ( $3^\circ$  to  $5^\circ$ )

The modern ATB using helical planet gears requires no maintenance. It is insensitive to the oil used, and has a very long life. In fact, RT Quaife Engineering LTD, one of the largest producers of the ATB differential, warrants their differential even when used for racing.

There are two further differentials that should be mentioned. These are of the “differential speed sensing” type. These differentials have of two types of actuation: viscous and hydraulic.

The viscous type differential looks internally similar to the Salisbury clutch pack type diff, except that the clutch plates and stators are sealed inside a capsule filled with a silicone based fluid. The silicone fluid’s viscosity increases with

shear rate, meaning that as the inside wheel starts to spin, the fluid thickens and causes the torque to be applied to the outside wheel.

The hydraulic speed sensing differential uses the differential in wheel speed to actuate a pump, which is ported to a piston compressing the Salisbury-type clutch pack, replacing the need for ramps.

Since the speed sensing differential requires wheel spin to actuate, it can only limit wheel spin, not eliminate it. Therefore, very high rates of tire wear on the inside rear will be experienced. Further, the hydraulically actuated clutch pack or viscous pack cannot share the load unless one wheel is spinning, unlike the Salisbury type. This severely limits their value for standing starts and for drag racing. Our shop has replaced number of viscous and hydraulic differentials that come in the Viper SRT10 and the Viper Competition Coupe with Quaife differentials. In most cases the stock differential gears were pitted, cracked, or broken because of the overload placed on these gears.

The benefit of the speed sensing differential is that it can transmit drive torque to the “good” wheel when one wheel is in the air. So they are used for drivers that hop the curbs hard enough to throw the inside wheels off the ground. Setup for these differentials is the same as for an open differential, as they do not lock.

## **CONCLUSION**

There are a number of differentials available for road racing. All have strengths and limitations, but the choices can be narrowed a bit. In our opinion, the desirability ranking would be as follows:

1. Open differential, if it can be used
2. Automatic Torque Biasing Differential
3. Salisbury type differential
4. Viscous or Hydraulic differential
5. Cam and Pawl differential
6. Spool
7. Detroit Locker

The final choice depends upon what is available, cost, and expertise, and perhaps what is already in the car.

*(Photos and diagrams not otherwise credited are provided by Taylor Race Engineering.)*



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