Torsen Differentials - How They Work and What STaSIS Does to Improve Them For the Audi Quattro

One of the best “bang-for-your buck” products that STaSIS has developed is the center differential torque bias modification. This relatively simple upgrade can make the already excellent Quattro system perform even better in demanding performance applications. In short, it allows you to deliver torque where you need it and when you need it.

In this two part article we will present the basics of how open and Torsen differentials work and then present the performance characteristics of the Torsen differential and what STaSIS does to improve it.

In order to understand the benefits of a STaSIS high-bias torsen center differential for Quattro cars, it is necessary to first understand the purpose and workings of a simple open differential. Open differentials are found in the front and rear of Audi vehicles equipped with Quattro all-wheel-drive as well as the majority of the cars on the road today.

Within the transmission of most Audi all-wheel drive cars, there is a center differential that supplies torque to the front and rear axles. The center differential is called a Torsen differential and while it serves a similar purpose to the open differential, its operation is much different.

Open Differential

In the early 19th century, Marcel Pecquer, a French railroad engineer, tackled the problem of how to deliver equal amounts of torque to two wheels that were spinning at different speeds. The same issue is present on any car on the road today and the most common example of this occurs when a car is driven around a turn. Consider the example in Figure 1. Looking at the front wheels, it should be apparent that the left wheel must turn faster than the right wheel because it has to travel further. This is not an issue in a rear wheel drive car because the front wheels are independent of each other. Now consider the rear wheels and let’s assume that they are connected by a solid axle. If the same logic holds true, the left rear wheel would want to go faster than the right rear, forcing either the right wheel to spin or the left wheel to drag.
A differential lets each wheel turn at its own speed while providing an equal amount of torque to each wheel – each wheel thus keeps its grip with the ground or railroad tracks, as the case may be. Torque can be defined as the force that causes rotation. The basic design for an open differential, has not changed much since 1827 when Pecquer first fitted one to a steam traction engine (see Figure 2). Additional benefits include: reduced power required for making a turn, decreasing turning radius, and smooth slip-free low-speed driving.

For the moment, we will assume that this differential is transmitting power from the transmission to the rear wheels of a rear wheel drive car. The input shaft (from the transmission) transfers torque directly to the differential housing via the outer ring gear. So-called “spider gears” rotate on a shaft that is attached to the inside of the housing. These impart torque to the left and right drive gears, which are rigidly attached to the drive axles via the left and right output shafts.
The simplest example to understand how the components work together is when both wheels are turning at the same RPM (Revolutions Per Minute). The input shaft spins the differential case, which in turn imparts torque from the spider gears to the drive gears. Since both drive gears are moving at the same RPM, the spider gears are not rotating around their own axes because they only rotate when there is a speed difference between the left and right wheels. The RPM and torque for each wheel are thus the same.

Now, suppose we are going around a right hand turn again. Remember, that the inside wheel, the right side in this example, travels less distance than the left side. In this case the right drive gear will be spinning slower than the left drive gear, thus forcing the spider gears to rotate around their own axes. This lets the sum of the drive gears’ rotational speed to remain the same while the torque is evenly split. While this is beneficial in many situations, more extreme circumstances highlight the weaknesses of an open differential.

Remember your high school physics? Newton’s third law tells us that “For every action there is an equal and opposite reaction.” Suppose the right wheel runs over a patch of ice while the car is traveling in a straight line – suddenly the force the car is able to impart is drastically reduced. The open differential applies the same amount of torque to each side. AND, the torque that it can deliver is limited to the amount of torque that won’t make the wheel slip. So if the right wheel is on ice, the torque that will make that wheel spin is very low. Remember that the torque delivered to both sides is the same, little torque is delivered to the left side with good traction.

Since we’re dealing in Audis here, let’s just suppose we had an open differential for a center differential. The maximum driving force available would then be (as above) that available by the lesser of the front or rear wheels. In low grip situations the car would be limited by one pair of wheels, even though the other pair might have decent traction. Fortunately, when Audi designed the Quattro system they realized that the front and rear pairs of wheels would greatly benefit from having a dynamic difference in torque.

**Torsen Differential**

The dynamic difference in torque in the Audi Quattro system is achieved with a Torsen (Torque Sensing) differential as the center differential. Torsen differentials have the unique property of handling different wheels speeds (between front and rear in the Quattro) while delivering the available torque (defined by both the engine and grip conditions) up to a specific ratio. In most Audi applications this bias ratio is approximately 2:1. Thus a car with 300 ft-lbs available could deliver 200 ft-lbs to the rear wheels and 100 ft-lbs to the front, or the opposite – 100 ft-lbs to the rear and 200 ft-lbs to the front.

A common misunderstanding about Torsen differentials is that there is a “static” ratio of 1:1. Torsen differentials are constantly adjusting the torque bias to existing conditions. If both the front and rear set of wheels have identical traction, this ratio would be 1:1; however, any difference in grip between the two will lead to a torque difference.
How Torsens work

Compared to the open differential described above (Figure 2), the Torsen differential (Figure 3) replaces the side and spider gears with element and spur gears. The spur gears function like the open differential’s side gears, and the element (also known as satellite) gears connect with the spur gears in a modified crossed axis helical gear mesh. Also known as an Invex gearing arrangement, it allows for continuous contact (decreasing wear and tear) and provides the main mechanism for achieving the previously mentioned torque bias.

The Invex gearing also has a unique characteristic in that the driving torque, which is delivered from the transmission to the Torsen housing, can be transferred from element gears to the spur gear but not the reverse. This driving torque causes the element gears and spur gears to “lock-up”, delivering the engine torque to the wheels. Conversely, the side gears can turn the element gears but not the reverse.

Using the same example of a right turn and assuming that the open differential has become a Torsen, the left wheel will turn the left spur gear faster than the Torsen housing. Conversely, the right wheel will turn the right spur gear slower than the Torsen housing. The speed difference is taken up in the synchromesh gear portion of the element gears.

Again suppose that the right wheel runs over a patch of ice and traction is reduced. Torque will be sent to the right wheel causing:

1. the right wheel to turn the right side gear faster than the Torsen housing that then,  
2. turns the right element gear which tries to turn the left element gear  
3. The left element gear then tries to turn the left spur gear
Refer back to the Invex gearing characteristics described above. When the element gear tries to turn the spur gear they will “lock-up” and the torque from the housing will be imparted to the left wheel. Note that in the above example the traction is reduced. The Torsen differential is a torque multiplier of the torque available from the wheel with less traction. It multiplies the available torque, by the bias ratio, to the slower turning wheel with better traction. This is important because if the wheel is in the air, traction is reduced to zero. Multiply by zero torque and the result is zero and nothing will move.

In the Audi Quattro, all of the above concepts hold true except that Quattro uses a Torsen to bias torque between the front and rear axles versus left to right as our examples have shown.

**Torsen Performance**

As mentioned before, on a smooth, straight road, Torsen performance would be identical to that of an open differential – equal torque balance between front and rear. In a situation where the front and rear have different traction available (such as in inclement weather or enthusiastic driving) the Torsen will deliver more torque to the set of wheels with more traction, limited only by the maximum bias ratio or the amount of traction available to that set of wheels. This is why Audi drivers are often seen with a smug smile as they pass SUVs and pickups in the snow.

While the Torsen differential provides great advantages in inclement weather and every-day driving, performance disadvantages become apparent during more aggressive driving while pushing the car to its limits. The STaSIS World Challenge Touring Car Team encountered these limits when originally building the B5 A4s to compete in 2001. Under hard braking (i.e. very little engine torque) the Torsen has very light internal loading, causing it to act much like an open differential, going into the turn with little drama. Powering out of the turn is an altogether different story. Under acceleration the weight is shifted rearward, giving the rear tires more grip while removing grip from the front tires. The factory Torsen (2:1 torque bias ratio) system compensates, sending approximately 66% of available torque to the rear tires and 33% to the front tires. This results in front wheel spin and not a great deal of torque to the rear wheels.

This torque bias thus handicaps the Audi in corner exit - the car can not put down its available power effectively, it loses available lateral acceleration due to wheel spin, and decreases tire life by spinning wheels needlessly. Rear wheel drive cars don’t have this problem, for they can put down all of their power through the rear tires and they don’t lose traction through front wheel spin.

For the enthusiast, then, the optimal solution would be to have a front wheel drive (FWD) car on corner entry, an all wheel drive (AWD) car mid-corner, and a rear wheel drive (RWD) car on exit. On corner entry, a FWD car would let the rear wheels spin freely under heavy braking, while in mid corner (essentially a steady state turn) an AWD car could put power down to all 4 wheels using all of the available grip on track. On corner exit, a RWD car could put all of its power through the rear while using the front tires for maximum lateral acceleration.
**STaSIS High Bias Torsen**

The STaSIS High Bias Torsen brings Audi enthusiasts close to this optimal solution. By modifying the frictional and geometric constraints within the Invex gear train, a STaSIS differential can achieve up to a 7:1 torque bias ratio. In terms of the optimal solution presented above, an AWD car fitted with a STaSIS differential will act like a FWD car in the brake zone (recall a Torsen acts like an open differential under small loads), while in mid corner under throttle the Torsen will send torque nearly equally to the front and rear wheels, and on exit up to 88% of the available engine torque will be sent to the rear wheels. This equates to 33% more power available to the rear wheels! The STaSIS high bias Torsen allows your car to make full use of the available grip AND available power.

While it’s a relatively simple modification, the STaSIS torque bias modification provides a dramatic improvement in negotiating a turn quickly and efficiently.