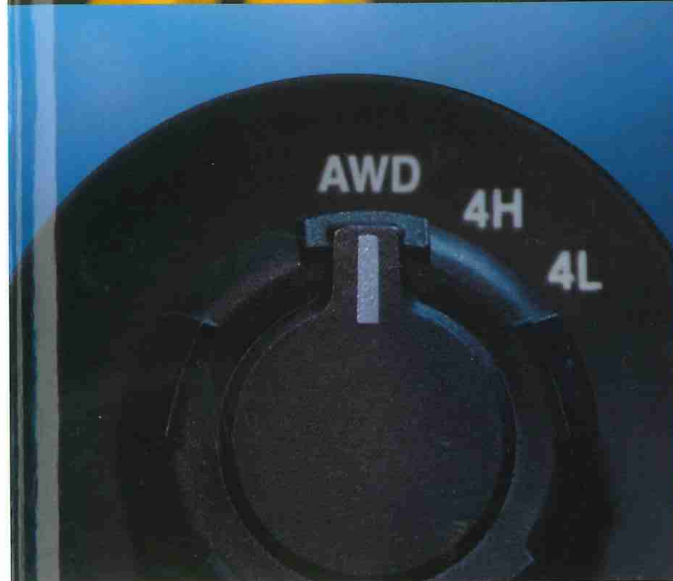


All-Wheel Drive Technology Inspiring Confidence

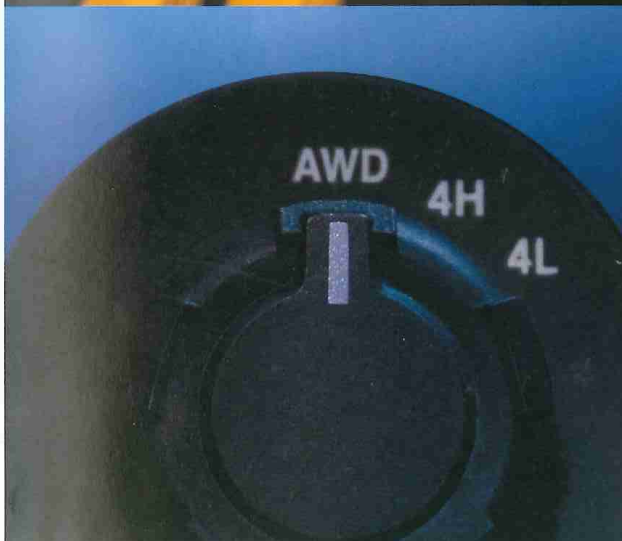
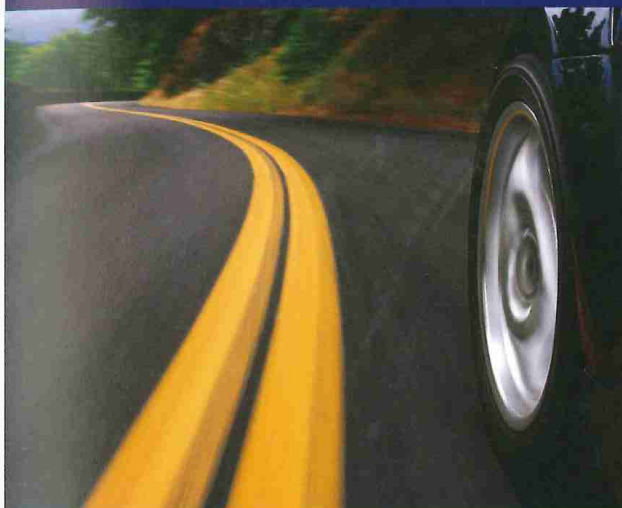


From a Global Leader in Drivetrain Technology

GKN 2037

 **BorgWarner**

All-Wheel Drive Technology Inspiring Confidence



From a Global Leader in Drivetrain Technology

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CHAPTER 1

By *Vernon P. Jones contributing Erika Nielsen*

EARLY HISTORY

The earliest version of an all-wheel drive system was first presented at the Paris Salon of 1903, when the Dutch company, Spyker, exhibited the first prototype featuring a mechanical drive to all four wheels at the same time. Although that car was never produced, many other manufacturers adopted the layout. Prior to Spyker's all-wheel drive prototype, there were some notable front-wheel drive predecessors such as Nicolas-Joseph Cugnot's 1771 Fardier a Vapeur "Steam Dray," and a 1898 design from Latil of France with power packs replacing the front axle, shaft and horse in carts.¹

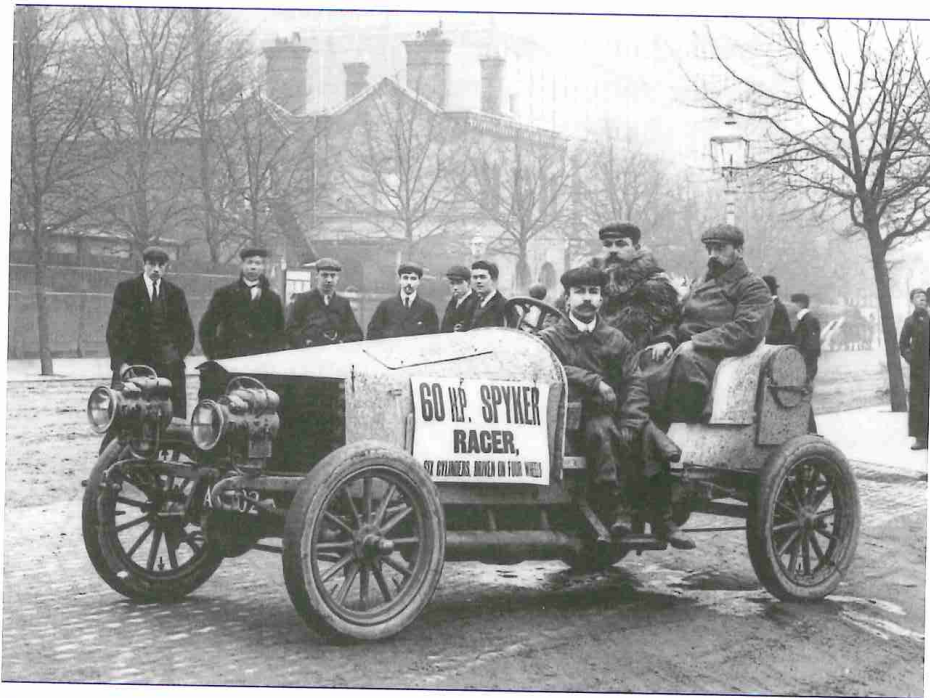


Figure 1.1: 1903 Dutch Spyker (Source: Go to http://www.conceptcarz.com/vehicle/z8564/Spyker_60_HP.aspx)

At the time of Spyker's prototype, and for a number of years to follow, one of the major problems with all-wheel drive vehicles was the lack of homokinetic (constant velocity) joints. The Cardan or Hooke joints available at the time allowed front-wheel steering, but

¹ Joseph Palazzolo, "Fundamentals of All-Wheel Drive Systems" (1997), 16–17.

the rotating motion was irregular (sinusoidal) and caused torque pulsations in the driveline that increased as the steering wheel was turned to full lock. Drivers found that front-wheel or four-wheel drive vehicles with non-constant velocity joints at the front wheels, especially those without inter-axle differentials, were extremely difficult to steer around tight corners because of the torque pulsations being fed back through the steering wheel.

Throughout the 1910s and 1920s a variety of on-road and off-road vehicles were produced, but front-wheel drive and four-wheel drive for on-road vehicles did not become practical until the Tracta and Rzeppa constant velocity (CV) joints were patented around 1927.² These patents were based in principle on a double Hooke joint and were used almost exclusively in all-wheel drive military vehicles by both the Allies and the Axis powers during World War II.

In fact, it was during World War II that the first real demand for all-wheel drive vehicles occurred. The U.S. military wanted vehicles that had greater off-road mobility and reasonable on-road performance. The ubiquitous Jeep satisfied both those needs.³

AWD ON-ROAD PASSENGER CAR DEVELOPMENT

It wasn't until after World War II, however, that anyone had a real interest in all-wheel drive on-road passenger cars. In the early 1950s the Ferguson Company in England (considered one of the premier leaders in early all-wheel drive) developed a system incorporating a differential splitting the torque of the transmission output shaft between the front and rear axles, while allowing for the difference in speeds between the front and rear wheels whenever the vehicle was turning. This system used a conventional bevel gear differential to split the torque equally. There was still the possibility, however, that on very slippery surfaces, one set of wheels could lose traction causing the available torque to go to the set of wheels with the least traction. To prevent this problem the early systems used two overrunning clutches, which locked up the drive whenever one set of wheels started spinning.

The Ferguson system was later simplified by using a single viscous coupling instead of the two overrunning clutches. This modification

² Alfred H. Rzeppa, "Universal Joint." U.S. Patent No. 1,665,280: 1927.


³ Will Fowler, *Jeep Goes to War*. (Philadelphia: Courage Books, 1992).



WW II Jeep

left the torque splitting differential virtually free for small differences in the rotating speeds of the front and rear wheels when cornering, but progressively locked the differential when the difference in speeds between the front and rear wheels became too great.

To demonstrate his system, Ferguson built a number of cars pioneering the layout later commercialized by Audi. In this layout the engine, mounted north to south, overhangs the centerline of the front wheels. The output shaft from the transmission, which contains the torque splitting differential, extends forward to drive the front wheels. A propeller shaft connects the rear axle to the torque splitting differ-



ential. The Ferguson cars were demonstrated widely, but without success. Apparently, the technology was too far ahead of its time.

A decade later, to demonstrate the advantages of all-wheel drive more convincingly, Ferguson built a Formula One racing car using a 1.5 liter Coventry Climax engine, called Project 99. The layout was more conventional. The engine was mounted longitudinally behind the front wheels and the gearbox containing the differential (from which propeller shafts drove the front and rear axles) was parallel to the transmission. Stirling Moss drove the car in the rain-soaked Gold Cup Race at Oulton Park in 1961 and literally ran away from the competition. Moss (and Ferguson's car) would have won another race that same year, had the driver not been disqualified for a minor infraction.⁴

Although Ferguson's racing car won the Gold Cup Race, the only manufacturer that took notice was Jensen. Subsequently, Ferguson converted the Interceptor to all-wheel drive to make the Jensen FF. This car used an epicyclic type torque splitting differential instead of a bevel gear type with 67% of the torque directed to the rear wheels and 33% to the front. Because of this torque distribution, the Jensen FF had the handling characteristics of a rear-wheel drive car.

AWD BOOM AND THE SUV

During the 1970s two manufacturers introduced vehicles worth noting. In 1972 Subaru mass-produced Leone, a part-time four-wheel drive system.⁵ And in the 70s American Motors Company introduced to their Wagoneer line Quadra-Trac, an automatic full-time four-wheel drive system.⁶ But many experts attribute the first boom in all-wheel drives to the Audi Quattro. This famous and historically significant road and rally car, introduced in 1980, was an impressive 200 bhp car that combined sports car performance, excellent comfort and remarkable safety.⁷ The 400 bhp rally version really brought home the virtues of all-wheel drive to the public at large. Although many critics felt all-wheel drive race cars were too heavy and complex, the Quattro was an instant success. It won a rally on its first outing and continued to win competition after competition for the next two years.

Even though the Audi Quattro is credited with starting the all-wheel drive boom, many consider the compact sport utility vehicles (SUVs), introduced in the early 1980s, the reason for the outright

⁴ Steve Small, *The Grand Prix Who's Who* (Aldermaston, U.K.: Travel Publishing, 1999).

⁵ <http://www.subaru-global.com/history.html>

⁶ http://www.jeep.com/jeep_life/legends/heritage/?section=0

⁷ <http://www.audiusanews.com/newsrelease.do?id=211>

explosion in all-wheel drive popularity. SUVs started to become popular in the United States during the mid-1960s as outdoor sports enthusiasts bought these vehicles to carry drivers, passengers and their gear directly to mountains and lakes. However, the SUVs available at the time were either too small or too crude (the Jeep CJ-5 and the International Harvester Scout), or too large (Jeep Wagoneer, Ford Bronco, Chevrolet Suburban and Blazer), to be practical. For drivers who wanted something a little sportier, or those who didn't want to use a step ladder to get in and out of their SUVs, there was nothing available.

Everything changed when manufacturers introduced the S-10 Blazer, the 1983 GMC S-15, the 1984 Ford Bronco II and the 1984 Jeep Cherokee.⁸ As the following chart (Figure 1.2) shows, it was after these introductions that the all-wheel drive market really took off. These new vehicles offered all the features people wanted in an SUV. They were functional, versatile, comfortable and practical. Thus consumers continued to be satisfied with these vehicles, that is until the arrival of the crossover sport utility vehicle.

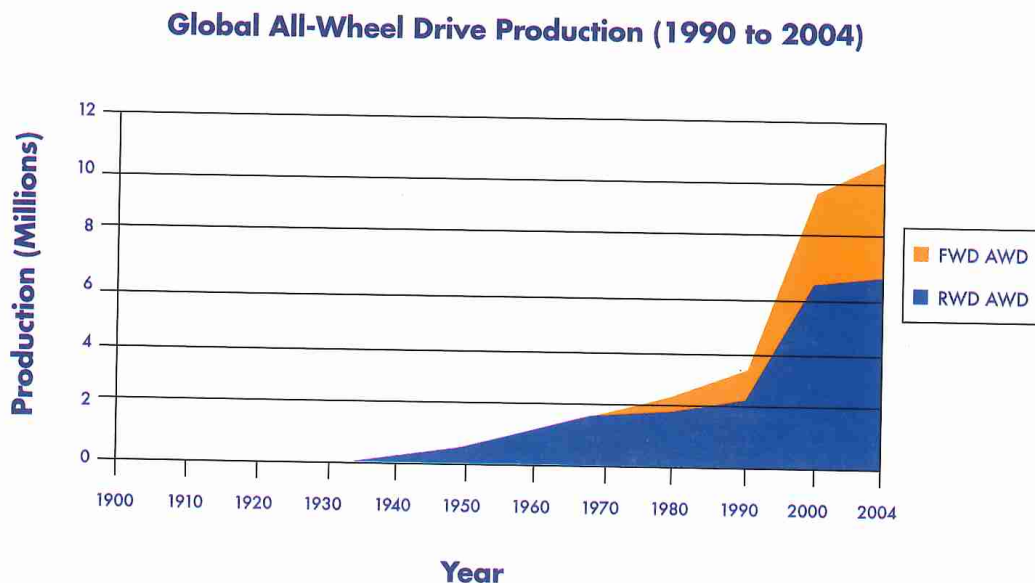


Figure 1.2: Early All-Wheel Drive Market (Source: BorgWarner, CSM, Global Insight, Drucker Research)

⁸ <http://www.edmunds.com/insideline/do/Features/articleId=46013>

The all-wheel drive SUV market peaked in 2000 but remained in high volume until 2004 when demand for a more car-like feel, and growing need for fuel efficiency, emissions reduction and globalization came to the forefront. (These market factors, as well as others, are discussed in detail in Chapter 2.) The 2004 shift in demand brought along the advent of the crossover sport utility vehicle (CUV). The CUV was built on a car's unibody construction instead of a truck's full-frame construction and had a more limited off-road capability, in some cases, compared to their SUV predecessors. Despite the fuel economy advantages of the CUV, consumers still demanded the stability, security and safety that all-wheel drive offered. So the market transformation began—in the developed regions of North America, Western Europe, Japan and South Korea—from rear-wheel drive based all-wheel drive vehicles to front-wheel drive based all-wheel drive vehicles.

CHAPTER 3

By *Larry Pritchard*

AWD BASICS

Before we begin a technical discussion of AWD systems, we need to first cover basic principles and terminology, which will be discussed in general here and in greater detail throughout the manual.

WHY AWD?

Historically, AWD was offered almost exclusively in pickup trucks and SUVs, which were purchased primarily for their cargo load limits and all-terrain capabilities (such as traction and mobility). In recent years the demand for AWD systems has expanded. Drivers of passenger cars and Crossover Utility Vehicles (CUVs) are demanding the technology for both traction and enhanced vehicle stability and handling. As the applications of AWD become more widespread, the technology becomes more complex, as is demonstrated in the next few pages.

The ability to accelerate a vehicle (assuming adequate torque at the driving wheels) is determined by the available traction (resistance to slippage or friction) between the tires and road or ground surface. Traction is a function of both the weight on the drive wheels and the frictional (resistance) properties of the road or ground surface.

Drive-wheel torque is a function of:

- Engine power (torque)
- Transmission gear ratio
- Torque converter ratio (if equipped with an automatic transmission)
- Low-gear ratio in the transfer case (if so equipped)
- The driving axle gear ratio (see Figure 3.1)
- Tire size

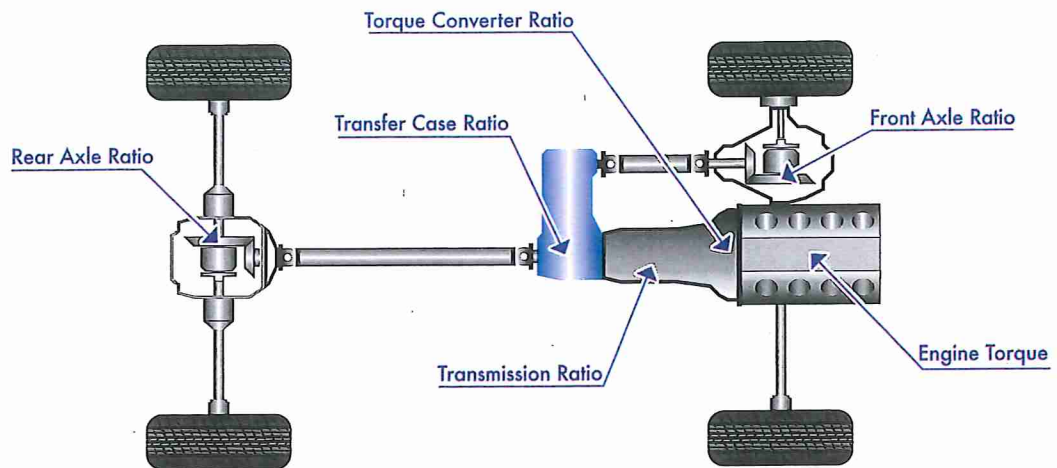


Figure 3.1: Typical RWD-Based AWD System

In a two-wheel drive (2WD) vehicle, torque is only applied to two wheels. If the drive wheel torque is greater than the available traction the wheels will “lose traction,” meaning they will break loose and start spinning. Even if only one of the wheels loses traction, the effective overall traction at the axle will be compromised if the axle is equipped with an open differential. As the driver negotiates a corner, the inboard and outboard wheels of a vehicle turn at different speeds due to the lengthened paths traveled by the outside wheels. The axle differential allows the wheels on each side of the drive axle to rotate at different speeds during cornering (see Figure 3.2).

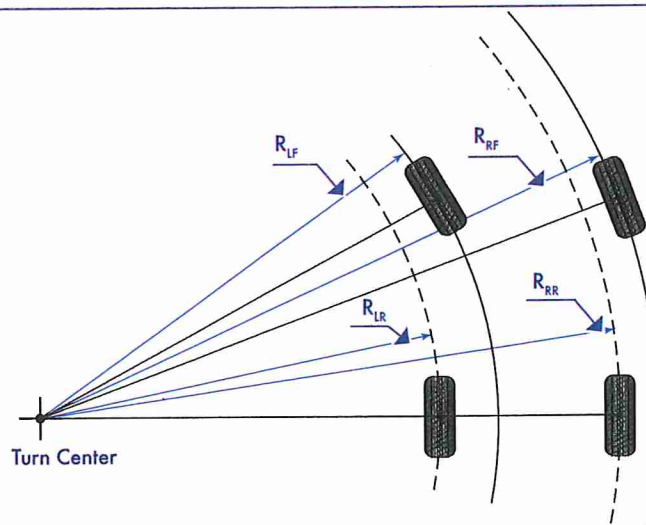


Figure 3.2: Wheel Speeds of a Rear-Wheel Drive (RWD) Vehicle in a Turn (Source: BorgWarner and Joseph Palazzolo)

In a 2WD vehicle with an axle differential, during a turn the outside wheel will rotate faster than the inside wheel. An open differential will distribute driving torque equally to both wheels. Therefore, if one wheel is on ice or snow or some other slippery surface (low friction) and the other is on asphalt (high friction), the maximum transferable torque is limited to the wheel on the low friction surface, which means the vehicle has insufficient traction to propel itself. To address this problem, a variety of limited-slip differentials (LSD) have been developed. These devices limit the slip of the faster spinning wheel and transfer torque to the non-spinning wheel or axle.

The loss of traction from any one wheel in a standard rear-wheel drive vehicle upon acceleration while cornering will usually result in oversteer. Oversteer is referred to as “fish tailing” or “looseness” in a RWD vehicle and will be discussed in greater detail in Chapter 11 (Vehicle Dynamics). Likewise, in a front-wheel drive vehicle this loss of traction upon acceleration while cornering will cause the vehicle to understeer. Understeer is referred to as “pushing” or “plowing” in a FWD vehicle and will be discussed in greater detail in Chapter 11 (Vehicle Dynamics).

In an AWD vehicle, the problems with low-speed traction and stability control are reduced. Also reduced are the directional stability and handling issues encountered at higher speeds. In an all-wheel drive system, this is accomplished by distributing the drive torque at the appropriate levels of slip to the ground or road surface through the use of all four wheels instead of two.

VEHICLE ARCHITECTURES

There are two basic vehicle architecture types: Front-Wheel Drive (FWD) and Rear-Wheel Drive (RWD).

FWD-Based

In a FWD-based architecture, the front wheels are used to propel the vehicle. In FWD vehicles the engine is typically mounted transversely, or what is more commonly known as an east-west powertrain layout (see Figure 3.3). There are, however, some FWD vehicles where the engine is mounted longitudinally (north-south), such as the Subaru Legacy and larger Volkswagen Automotive Group models (Audi A8, VW Passat).

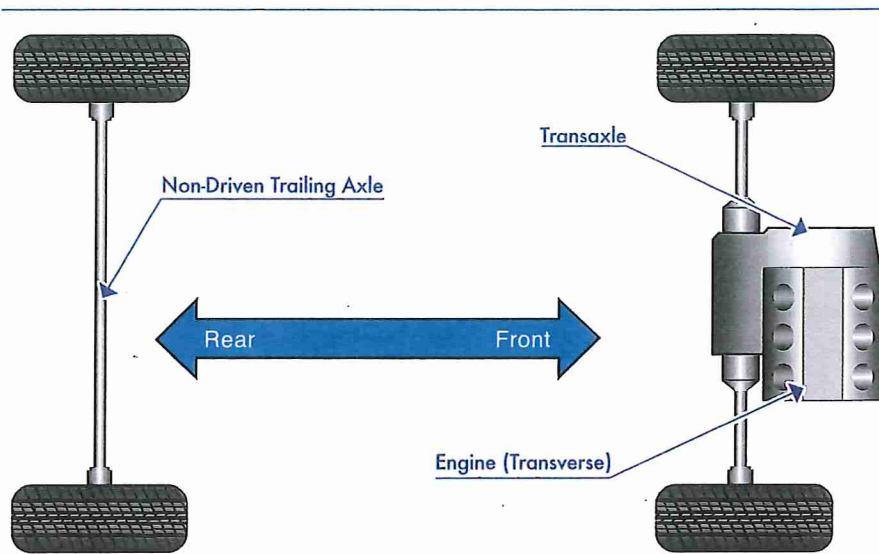


Figure 3.3: Front-Wheel Drive (FWD) Architecture

FWD vehicles have a transmission and axle combined in a common gearbox known as a transaxle (see Figure 3.4).

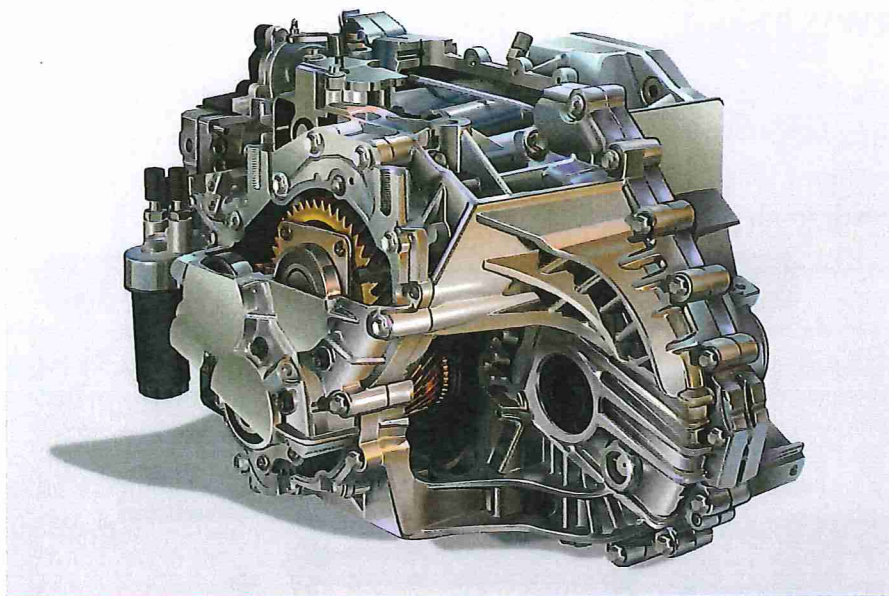


Figure 3.4: Example of Getrag Front-Wheel Drive (FWD) Transaxle (Source: BorgWarner)

FWD-Based AWD

In order to adapt the front-wheel drive vehicle to AWD, a power transfer unit is mounted to the differential case of the transaxle (see Figure 3.5). This unit takes rotational motion from the transaxle and turns it 90 degrees to drive a longitudinal propshaft that is attached to a secondary axle through a torque coupling device.

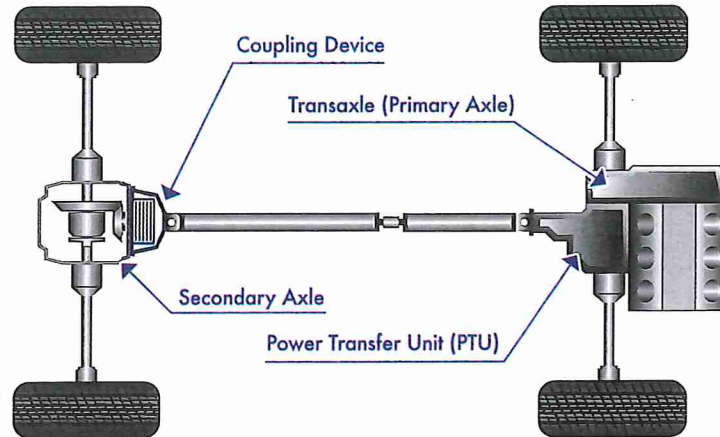


Figure 3.5: Typical FWD-Based AWD Architecture

RWD-Based

In a RWD-based architecture, the rear wheels are used to propel the vehicle. The vehicle powertrain layout is such that the engine is mounted longitudinally in the vehicle, more commonly known as a north-south powertrain layout (see Figure 3.6).

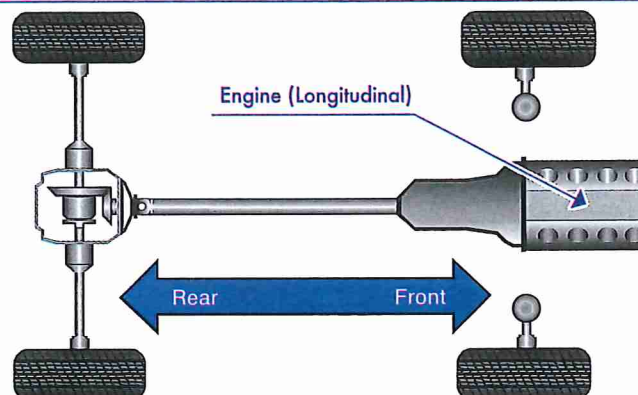


Figure 3.6: Rear-Wheel Drive (RWD) Architecture

RWD-Based AWD

In order to adapt the rear-wheel drive vehicle to AWD, a transfer case (transfer cases are discussed in more detail in Chapter 5) is required to transfer power from the transmission to the front secondary drive axle. Typically in a RWD-based AWD vehicle, a transfer case is mounted between the transmission and rear axle. The function of the transfer case is to transfer and manage torque from the transmission to both the front and rear axles. A chain or geartrain (usually helical gears) is used to drive the front axle. Some transfer cases have a low-range drive position for improved gradeability and ground speed control for off-road usage. Most transfer cases also have some type of torque management device to control the torque distribution to the front and rear axles. Figure 3.7 depicts the use of a transfer case in a typical AWD layout with a longitudinal engine.

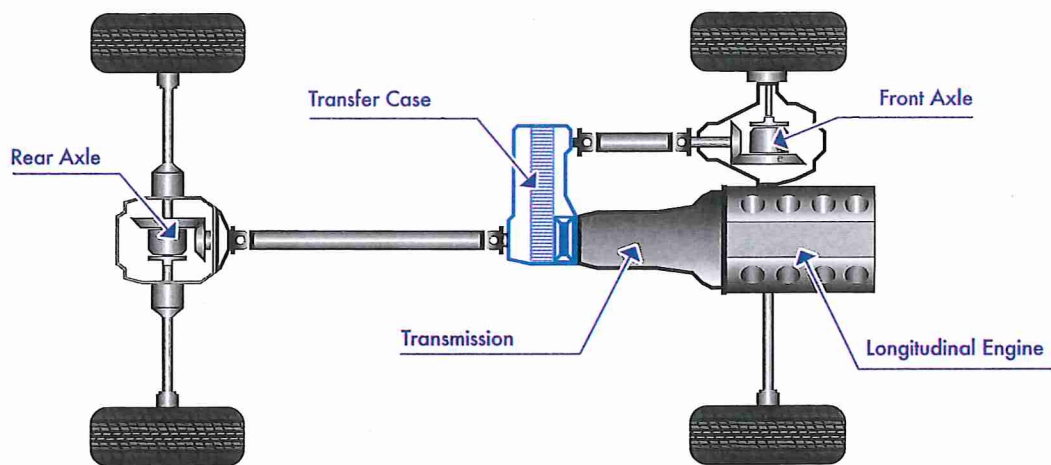


Figure 3.7: Typical RWD-Based AWD Architecture

Another AWD driveline architecture which should be mentioned is the so-called integrated AWD architecture found on Subaru and certain Audi vehicle applications. These driveline layouts incorporate the front drive differential as well as the torque management device within a longitudinal transmission. The engine is also longitudinal in orientation. Figure 3.7a is an example of such a driveline.

This type of architecture does not use a Power Transfer Unit (PTU). The function of the front propshaft is incorporated in the longitudinal transmission.

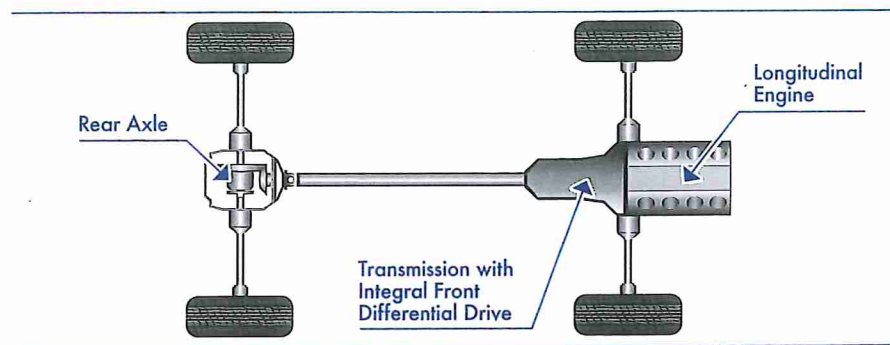


Figure 3.7a: Typical Integrated AWD Architecture with Longitudinal Transmission

This manual will focus on the more common AWD layout of the previously discussed FWD-based and RWD-based AWD architectures.

AWD VEHICLE USAGE—ON ROAD AND OFF ROAD

Now that we have a general understanding of the basics of AWD, let's examine how AWD vehicles are used, starting with off-road vehicles.

Traction—Mobility

AWD was initially confined primarily to trucks and special purpose vehicles having off-road capability. AWD vehicles are also commonly used to tow and haul heavy loads. Drivers of off-road vehicles expect that they can confidently go on, through or over almost any terrain (including climbing steep grades) without getting stuck. During off-road operation AWD vehicles are typically driven at slow speeds on low-friction surfaces such as dirt, mud, gravel, sand, ice and snow and up and down significant grades. The ability of a vehicle to traverse obstacles and/or difficult terrain is best described as "mobility."

The key factors affecting vehicle mobility (see Figure 3.8) include:

- Obstacle clearance (angle of approach, breakover angle, suspension travel)
- Maneuverability (turning radius, ground speed control)
- Gradeability (ability to climb a grade)
- Traction (tire tread pattern/construction, locking axle or axles)

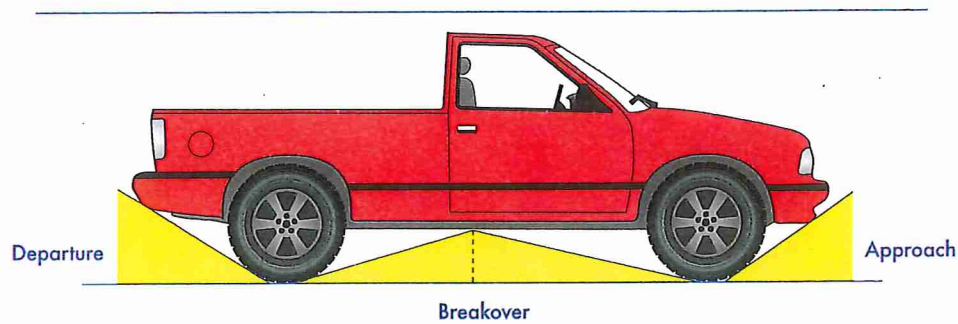


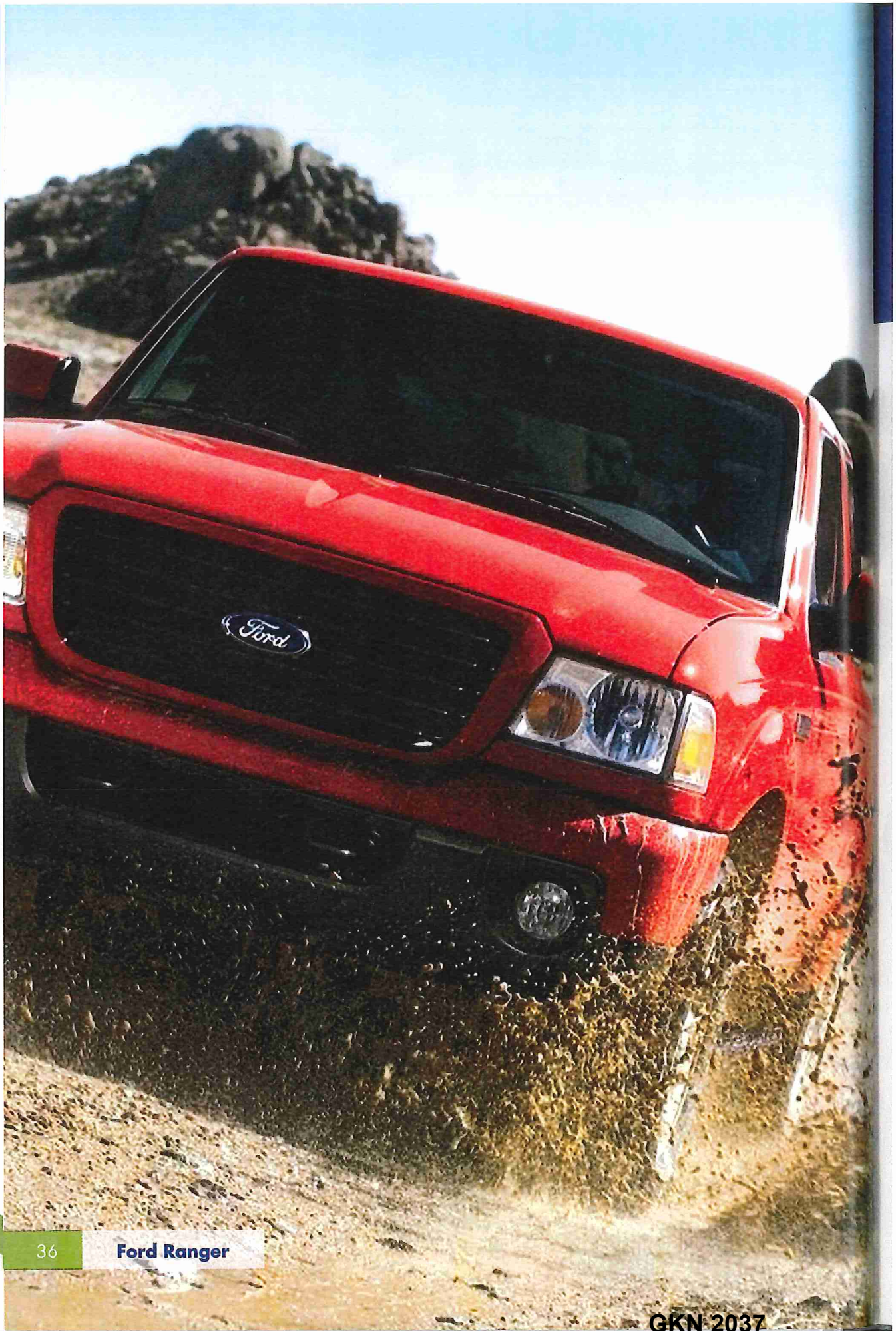
Figure 3.8: Obstacle Clearance Angle Example (Source: BorgWarner and Joseph Palazzolo)

Stability—Handling

While mobility (primarily longitudinal traction) is an important consideration for off-road vehicles, there is a greater emphasis on making on-road vehicles “fun to drive” (fast cornering, a total feel of the road and response) and “safe to drive” (handles well during all weather conditions, stability). Handling and directional stability are, therefore, the primary areas of focus for on-road vehicles. Handling commonly refers to the directional stability and controllability of a vehicle. In technical terms, handling generally refers to the behavior of the driver/vehicle combination in maneuvering tasks.

Directional stability is the ability of a vehicle to maintain its course (remain in a steady state) or remain under normal steering control while subjected to directional disturbing influences such as crosswinds, camber changes or braking on irregular surfaces. All of these principles will be explained in greater detail in Chapter 11 on Vehicle Dynamics.

If vehicles were operated strictly in either off-road or on-road conditions, the issues facing automotive engineers would be greatly reduced. But unfortunately this is not the case in today’s world where a number of AWD vehicles will experience both on- and off-road operation in varying degrees. This is especially likely for pickup trucks, SUVs and CUVs. The ability to develop systems that can be used in both on- and off-road vehicles to meet traction, directional stability and handling requirements presents a real challenge. Operating on loose dirt, gravel and sand surfaces presents different challenges as compared to on-road surfaces. Throughout this manual, we will examine the various drivetrain and chassis systems that can be employed to satisfy these diverse requirements.



CHAPTER 4

By *Larry Pritchard*

AWD SYSTEM CLASSIFICATION

With the increasing growth of AWD vehicles, especially front-wheel drive based CUVs, a number of different product/technology names are being used within the industry, causing confusion for the car buyer. Most of these terms are coming out of the OEMs' marketing departments. To address this issue, the Society of Automotive Engineers (SAE) AWD Standards Committee created a set of universal definitions (standard J1952) to describe these various systems. Three distinct sub-systems have been established: part-time, full-time and on-demand. Each system type has specific characteristics and modes of operation that are explained in the next few pages. It is also possible for a system to combine modes from some or all of these three systems—for example, a system that has four modes: 2H, 4H, A4WD and 4L. All four of these modes can be driver-selected. Thus, the type of system function is dependent upon which mode the driver selects.

PART-TIME AWD

Part-time AWD usually has a number of different operating ranges (high, low and neutral) and modes (two-wheel and four-wheel) and is typically used in truck/SUV applications. The driver may select two-high, four-high, four-low and neutral. The fundamentals of these operating ranges are described in greater detail in Chapter 5 (Transfer Cases).

Two-high is normally used when driving on paved, dry roads. In two-high only one axle (one set of wheels) is being driven (two-wheel drive). Four-high is used when additional traction is required, such as driving on ice or snow-covered roads or when operating off-road where the terrain is relatively flat without significant irregularities. In four-high, both axles (driving all four wheels) are mechanically connected and driven.

In four-low, additional torque is provided to both axles through the use of a low-range gearset. This additional torque is usually in the range of 2:1 to 4:1. Four-low is used for driving off-road where it is necessary to climb or descend steep grades or traverse rough terrain such as ditches, boulders, streams and so on. Neutral is only used when the vehicle is being towed.

In a part-time AWD vehicle, the driver has to manually select between the different ranges/modes. This is accomplished by moving either a floor-mounted shift lever or a dash-mounted switch or button. Some vehicles utilize a combination of both.

With part-time AWD, it is possible for a dangerous and damaging condition called “crow hop” to occur. With a part-time AWD transfer case, drivers should avoid driving on dry roads, in either four-low or four-high range. This is because the front and rear wheels are locked together, which prevents the front and rear wheels from turning at different speeds. In a turn, the front and rear wheels turn at different speeds due to the difference in the radius of turn for the front and rear wheels, see Figure 4.1.

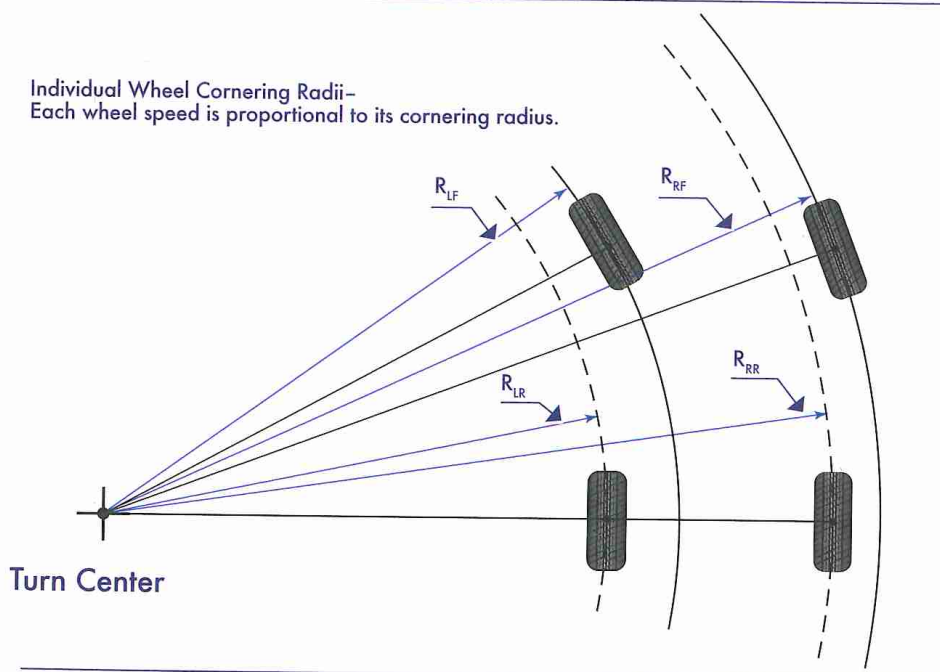


Figure 4.1: Wheel Speeds of RWD Vehicle in a Turn (Source: BorgWarner and Joseph Palazzolo)

In a low-speed turn, such as when parking, the tires scuff from torque reversals as the front and rear propeller shafts rotate at different speeds, resulting in torque windup in the system. The vehicle bounces around and moves in an uneven fashion (both forward and side-to-side) due to the build-up and release of torque in the system as the tires stick and slip. This motion, which looks much like that of a hopping crow and is, thus, referred to as “crow hop,” can cause damage to the vehicle’s driveline.

FULL-TIME AWD

In a full-time AWD vehicle, AWD is always engaged and delivers a fixed torque distribution to the front and rear axles. In most cases, the driver does not have to do anything unless the system has low range and/or a way to lock the front and rear axles together (like a part-time system) for serious off-road usage.

The distinguishing feature of full-time AWD systems is the inter-axle (center) differential, which allows the front and rear axles to rotate at different speeds. This eliminates the torque windup, and resulting “crow hop” that occurs when part-time systems are operated in four-high or four-low mode on dry paved surfaces (high coefficient of friction). The inter-axle differential is a system of gears that can compensate for the difference in speeds between the front and rear axles.

The center differential allows for the difference in speeds between the front and rear axles, but it has a significant disadvantage—it sends power to the axle with the least resistance (traction) to movement. For instance, if the front wheels of a vehicle equipped with a full-time system with an open differential are on ice (low traction) and the rear wheels are on asphalt (high traction), all the power will be distributed to the axle with the least resistance, in this case the front wheels will spin or slip—preventing the vehicle from moving. This undesirable condition can be eliminated by mechanically locking the differential, thus achieving the traction performance of a part-time system. While this solution works well for vehicles that are being driven off-road, it is far from ideal for on-road driving.

To make the full-time AWD systems more user-friendly and to eliminate the need for the driver to determine which mode is best for the driving conditions, most manufacturers use some form of torque management system. These torque management systems range from passive torque-sensing or speed-sensing units to fully electronic computer controlled clutch actuation systems across the differential. While not as capable as a manually locked center differential, they are more than adequate for vehicles that see limited off-road usage or are driven by “soft off-roaders.” Some manufacturers offer systems with a combination of automatic as well as driver-selected torque management systems. More recently, manufacturers started offering systems that involve the use of the anti-lock brake system technology to provide traction management by controlling the amount of slip at each wheel. These various torque management technologies will be discussed in greater detail in Chapter 8 on Torque Management Devices and in Chapter 11 on Vehicle Dynamics.

ON-DEMAND AWD

On-demand AWD vehicles operate primarily in two-wheel drive. They only operate in AWD drive as needed, or “on-demand.” For example, if the rear wheels of a rear-wheel drive based AWD vehicle are on a slippery surface and the front wheels are on a high resistance surface such as asphalt, the rear wheels will slip when the power is increased until a predetermined set of conditions are reached (amount of wheel slip, steering angle, etc.), at which point power will be transferred to the front wheels. There are also front-wheel drive based AWD systems where the rear secondary axle is engaged on-demand. Some on-demand systems can also operate preemptively: that is, the torque transfer device can be engaged before wheel slip occurs or any vehicle instability is felt by the driver. This preemptive action occurs through the use of computer controls that respond to inputs such as throttle angle, vehicle speed, steering wheel angle and others to effectively turn the device “on” in a preemptive fashion.

The “active” torque management coupling devices used in these on-demand systems engage and disengage rapidly to avoid any

driveline windup. These active systems can also be integrated with electronic stability programs to provide fuel-efficient vehicles with superior handling and stability, such as on the GM Cadillac CTS (RWD/AWD) and the Hyundai Santa Fe (FWD/AWD).

COMBINATION AWD

The Isuzu Trooper and the Ford Expedition have systems that combine the features of several systems.¹ The Expedition uses a BorgWarner transfer case (44-16 featured on the Ford Expedition and Lincoln Navigator) that combines the features of both part-time and on-demand systems (see Figure 4.2). The operating modes are 2H, A4WD, 4H and 4L.

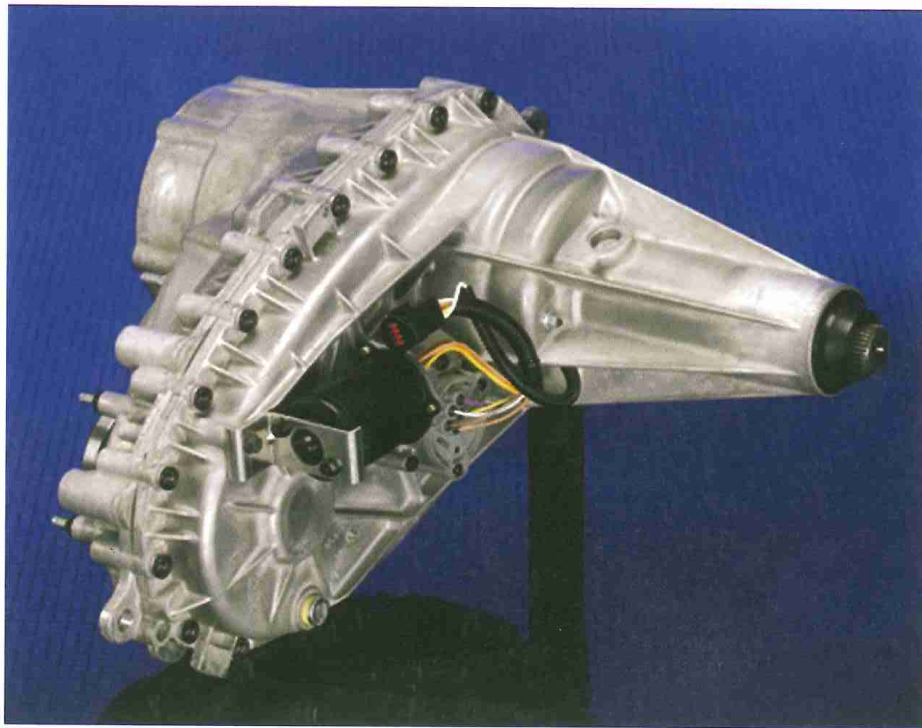


Figure 4.2: BorgWarner 44-16 Transfer Case Featured on the Ford Expedition and Lincoln Navigator

¹ It should be noted that the Isuzu Trooper was the first such vehicle implementation, followed years later by Ford. Both vehicles used BorgWarner technology.

CHAPTER 9

By John A. Barlage contributing Joseph Palazzolo

DRIVELINE DISCONNECT SYSTEMS

In this chapter, various driveline disconnect systems are discussed. Center disconnect systems and various wheel-end mechanisms provide a means to disconnect the secondary axle from the driveline. These systems are typically used on some part-time and on-demand transfer cases.

The disconnect feature can improve fuel economy because key components are no longer rotating and therefore are not contributing to parasitic losses. In addition, noise, vibration and harshness (NVH) performance can be improved since the front propshaft is not rotating when the system is disconnected. All these disconnecting methods require a coordinated action within the transfer case to disconnect the front output, thereby disconnecting the front propshaft.

There are various methods to disconnect the secondary driveline ranging from a complete disconnect at the wheel hubs to a partial disconnection of only some of the driveline components.

There are three typical methods to achieving a specific level of driveline disconnect:

1. Center disconnect
2. Inter-axle disconnect
3. Automatic hub locking systems

CENTER DISCONNECT SYSTEMS

When the transfer case is in the two-wheel drive mode, a center disconnect axle system uses a sliding collar (dog clutch) arrangement to disconnect one of the axle shafts from the differential side gear. The opposite axle shaft is still connected to a side gear which will drive the differential gears (but not the ring and pinion gears), preventing

CHAPTER 10

By John A. Barlage

TORQUE MANAGEMENT DEVICES FOR CROSS AXLE CONTROL

This chapter will review limited-slip axle differential (LSD) technologies that are typically found in today's originally equipped vehicle applications. Several performance aftermarket LSD and lock-up differential technologies are also available, but these will not be discussed in this manual.

THE OPEN AXLE DIFFERENTIAL

As mentioned earlier in this manual, vehicles equipped with open differentials can be at a severe disadvantage, from a traction standpoint, when operating on slippery surfaces or in off-road conditions. Because the open differential can only transmit as much torque to the high traction wheel as is available at the low traction wheel, the vehicle is at a disadvantage when driving on slippery

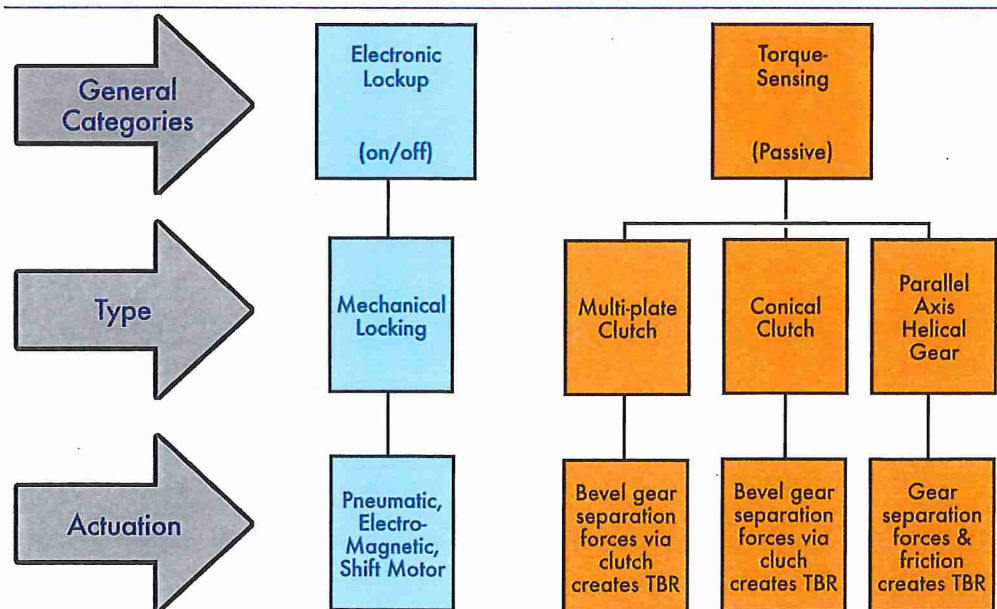
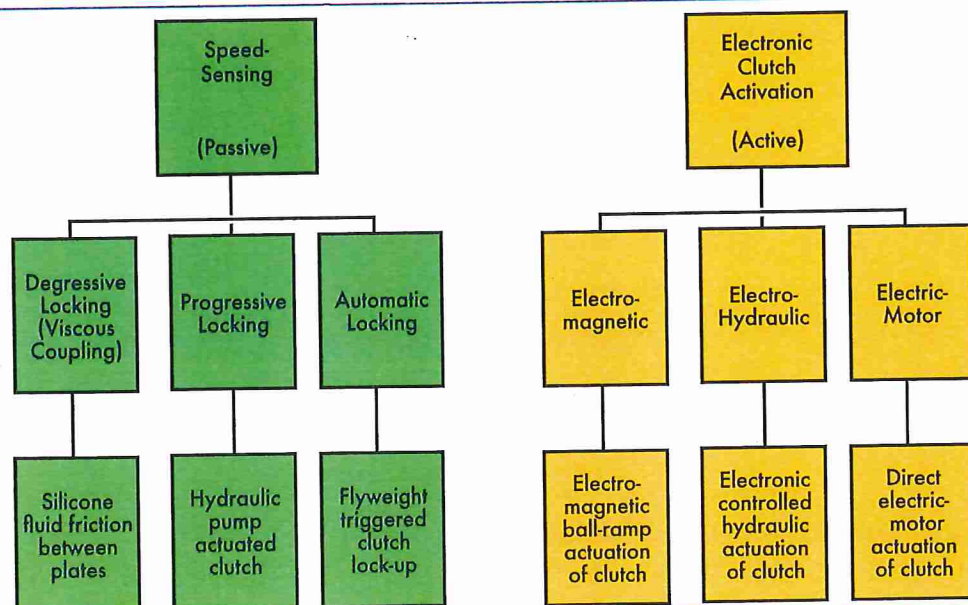


Figure 10.1: Overview of Typical OEM Equipped Limited-Slip Axle Differential (Source: Courtesy of GKN Driveline)



surfaces (ice, snow and rain) or when one wheel is off the ground. In principle, an all-wheel drive system is only as good as its worst axle differential. Although brake-based traction control systems do mitigate some of the shortcomings of the open differential, limited-slip differentials provide significant improvement in traction capability as well as contribute to vehicle handling and stability enhancements.

There is a wide variety of limited-slip differential technologies with unique performance attributes ranging from electronic lock-up to passive (torque-sensing or speed-sensing) and electronic clutch actuation (see listings in Figure 10.1).



ELECTRONIC LOCK-UP DIFFERENTIAL

The electronically actuated lock-up differential provides the ultimate traction solution for extreme driving conditions. The device is either fully locked by a mechanical connection or is in an open state (no variable mode). Typically one side gear is mechanically connected to the differential case resulting in a rigid connection between the right and left wheel resulting in no speed differential between the wheels. Because of this, the system should only be activated under extreme conditions such as off-road driving. Mechanically locking actuation can be by air pressure (air pump), electromagnetic or electric motor. An example of one type of electronic lock-up differential (electromagnetic actuation) is shown in Figure 10.2

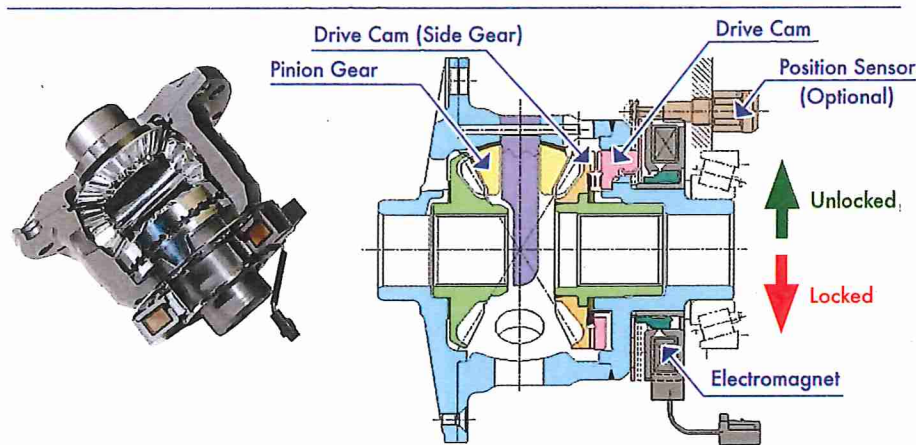


Figure 10.2: Electronic Lock-Up Differential Example (Source: Courtesy of GKN Driveline)

Historically, these types of locking differentials have only been available via the performance aftermarket, but recently manufacturers have begun offering this feature (as standard or optional equipment) on production vehicles in both rear and front axle applications.

Passive Torque-Sensing LSD

Passive torque-sensing limited-slip axle differentials are designed to resist speed-difference through mechanical friction. This resistance to speed difference is characterized by its torque bias ratio (TBR) performance. The operating principle of torque-sensing differentials is explained in Chapter 8.

There are basically three types of torque-sensing limited-slip differential used for axle applications:

1. Multi-plate clutch
2. Cone clutch
3. Geared type

Each of these systems has specific performance attributes which must be considered with respect to vehicle level performance targets as well as cost.

Multi-Plate Clutch Torque-Sensing LSD

The multi-plate clutch type is the most popular of the preloaded clutch designs. The clutch packs consist of flat hardened steel plates with various oiling grooves (or other friction materials) and are located between the differential and each side gear and differential case. Half of the plates are splined to the side gears and the other half are splined (or tabbed) to the differential case. The clutch packs are preloaded by a single coil spring, a group of coil springs, an S-shaped spring or one or more Belleville springs. Based on the reactive torque at both wheels, the resulting gear separation forces between the pinion and side gears produces a thrust force that, combined with the preload force, compresses the clutch pack limiting the amount of wheel slip. Lubrication of these differentials is critical because the plates slip each time the vehicle turns a corner. A special friction modifier is used to improve the performance of the lubricant to eliminate a “stick-slip” condition normally associated with differentials of this type. An example of this type of LSD is shown in Figure 10.3.



Figure 10.3: Multi-Plate Clutch Type Torque-Sensing LSD Example (Source: Courtesy of GKN Driveline)

Cone Clutch Torque-Sensing LSD

Cone clutch type preloaded designs are similar in construction and operation to the flat multi-plate design—except cone type clutches are used. An example of this type of LSD is shown in Figure 10.4.

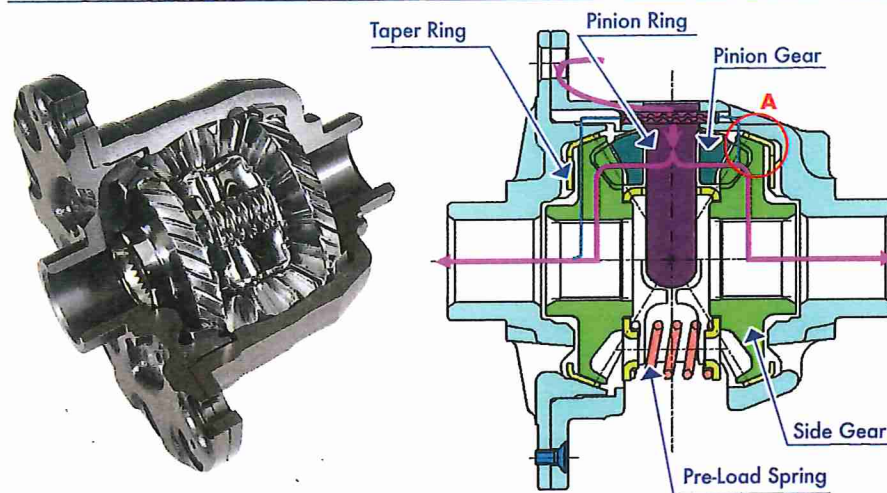


Figure 10.4: Cone Clutch Type Torque-Sensing LSD Example (Source: Courtesy of GKN Driveline)

Geared Type Torque-Sensing LSD

Geared type torque-sensing limited-slip differentials use specific helical or worm gear geometries and orientations to develop mechanical friction. The most common type of geared type LSD is the parallel axis type as shown in Figure 10.5. The unique feature of this type of LSD compared to the multi-plate or cone-type LSD is the frictional forces that are generated across many different components. These frictional forces allow for a more consistent TBR performance and gear backlash for the lifetime of the vehicle application. Additional thrust surfaces (similar to clutch plates) and preload features can also be added to the design.

The system can also be configured to provide different drive/coast TBR characteristics that can further tailor certain vehicle handling behaviors. The working principle of this type of LSD is explained in Chapter 8.

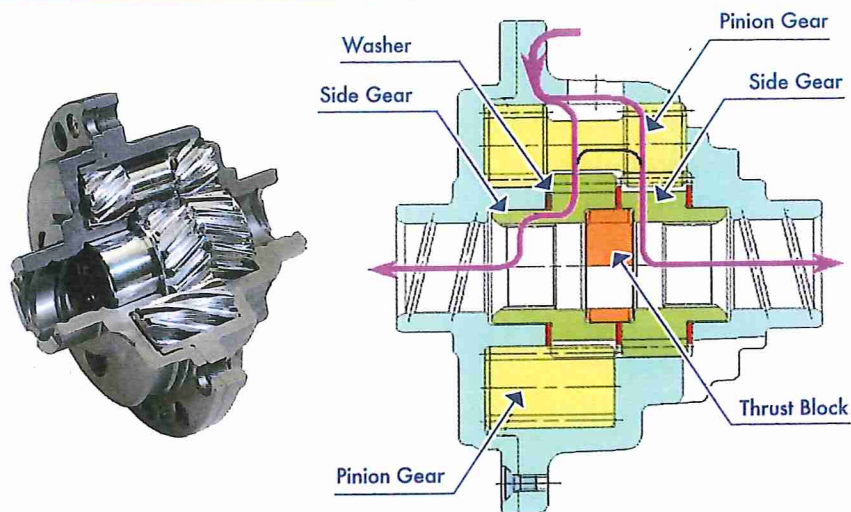


Figure 10.5: Parallel Axis Gear Type Torque-Sensing Differential Showing Frictional Contribution of Components (Source: Courtesy of GKN Driveline)

Passive Speed-Sensing LSD

Speed-sensing LSDs are very different from torque-sensing LSDs in that they respond to a speed-difference independent of what torque might be available. These systems generate a locking torque based on the speed difference and transfer torque to the wheel with the best traction potential.

There are typically three different methods to create a passive type differential:

1. Fluid friction
2. Hydraulic pump clutch actuation
3. Mechanical locking

All these systems are passive in operation in that they have no external control. Their particular torque vs. speed difference characteristics must be tuned to accommodate all driving conditions while providing acceptable drivability.

Fluid Friction Type Speed-Sensing LSD

The most common type of axle LSD using fluid friction is the viscous differential. In this differential the inner and outer steel plates are arranged alternately in a fluid-filled housing so that the outer plates are connected to the differential case and the inner plates to one of the side gears. The gap between the plates is filled with a high-viscosity fluid and the differential housing is sealed off with special seals, ensuring that one filling of silicone fluid will suffice for the lifetime of the differential. Figure 10.6 shows a typical cross section of a viscous axle differential.

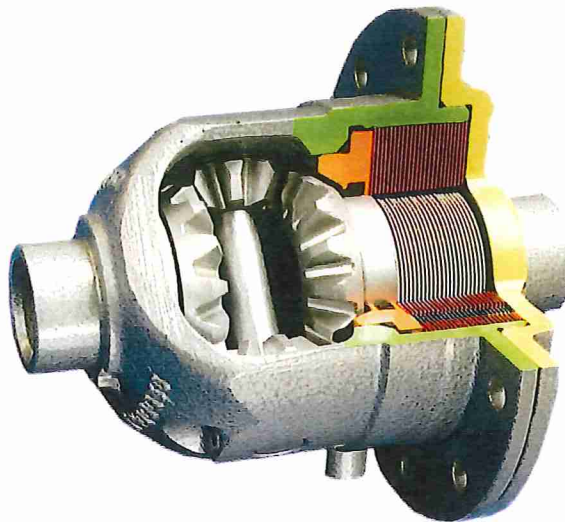


Figure 10.6: Viscous Axle LSD Cross Section (Source: Courtesy of GKN Driveline)

There are two operating modes in a viscous differential which are explained in Chapter 8.

Because this is a passive device, the torque characteristics selected must cover both winter and summer driving conditions as well as minimize tight corner binding.

Hydraulic Pump Clutch Pack Actuation Type Speed-Sensing LSD

There are several different mechanizations using a hydraulic type pump to develop hydraulic pressure in response to a speed difference. This resulting hydraulic pressure is then applied to engage a clutch pack which then provides a progressive locking torque across the wheels. Two typical methods of generating hydraulic pressure are:

1. Mechanical pump type
2. Shear pump type

Mechanical Pump Type Speed-Sensing LSD

A mechanical pump type system typically uses a gerotor type pump, combined with an apply piston and a set of friction-based clutches. The pump housing is connected to the differential case and the rotor is connected to one of the side gears. When there is a speed difference across the axle, the pump begins turning and fluid flow is initiated. The resulting pressure is then directed to an apply piston that will in turn press against a clutch pack. The working principle of this type of clutch actuation is explained in Chapter 8. A typical example of this type of axle LSD is illustrated in Figure 10.7.

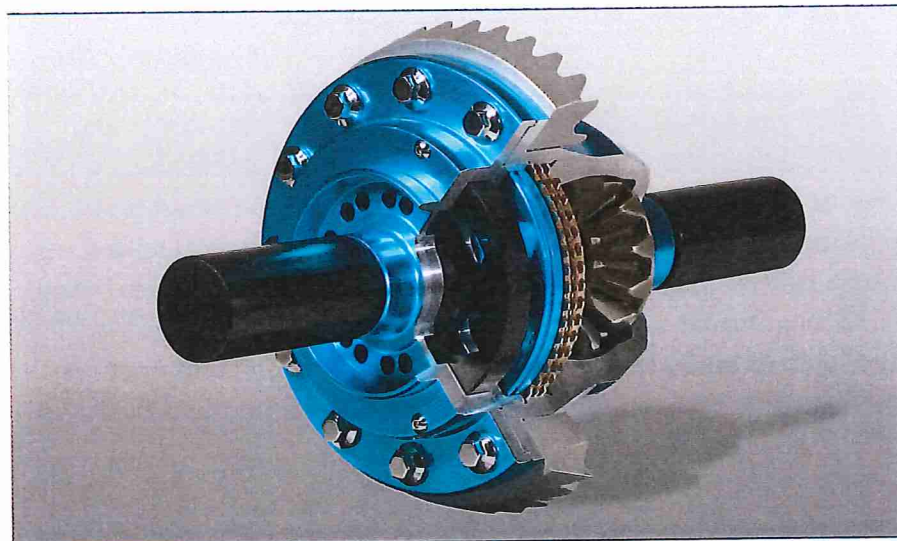


Figure 10.7: Gerotor Type Passive Progressive Axle LSD (Source: Courtesy of Joseph Palazzolo)

Shear Pump Type Speed-Sensing LSD

Another method to create progressive speed-sensing LSD is to use a viscous shear pump system in place of the previously mentioned gerotor type pump. The differential design includes a viscous shear pump and reservoir, apply piston and a set of friction based clutches (as shown in Figure 10.8).

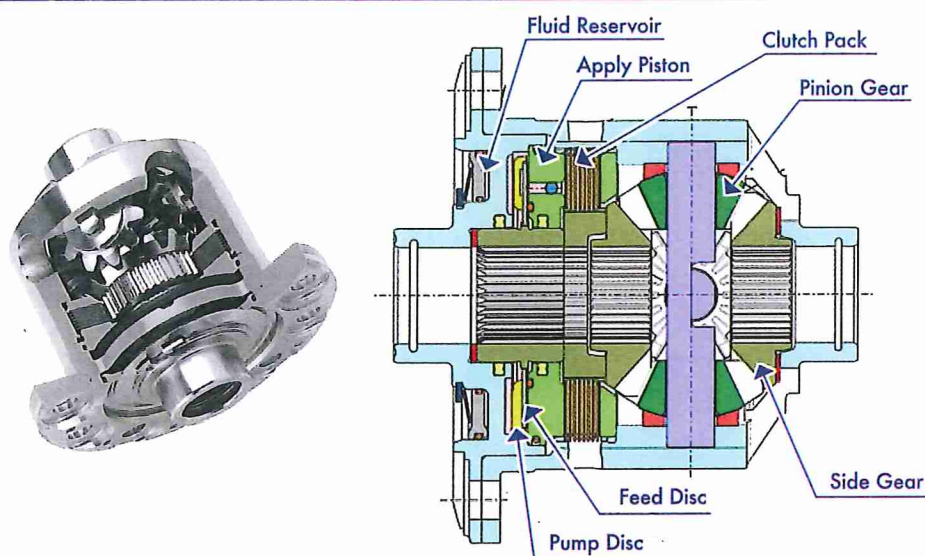


Figure 10.8: Shear Pump Type Passive Progressive Axle LSD (Source: Courtesy of GKN Driveline)

Key components of the shear pump are the housing, pump disc, feed disc, hub, apply piston and volume compensation piston. The pump is 100% filled with silicone fluid and has a self-contained fluid reservoir. The reservoir is sealed off with a compensation piston, allowing for fluid thermal expansion.

The pump disc includes a circumferential pumping groove and connecting holes forming the shear channel in conjunction with the feed plate. The pump disc is connected to the differential case and is allowed to self-index for bi-direction functionality. The feed disc is connected to one of the side gears. When there is a speed difference across the differential, there is a resulting speed difference across the fluid-filled channel. Fluid friction pulls fluid from the reservoir through the channel and generates the apply

pressure against the apply plate which then engages the clutch. Figure 10.9 illustrates the basic working principle of the shear pump.

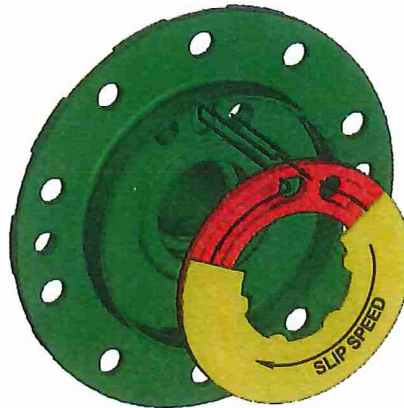


Figure 10.9: Viscous Shear Pump Working Principle (Source: Courtesy of GKN Driveline)

A key advantage of this system is that it has a self-contained reservoir so it does not scavenge hypoid gear oil as is required of gerotor pump based systems. Another advantage of the shear pump system is that no check valves are required because the pump disc self-indexes for bi-directional operation.

Mechanical Locking Differential

The mechanical locking differential is a unique device. It features a speed sensitive design that mechanically reacts to wheel slip by sensing when one wheel is spinning faster than the other. The system consists of the following major components: a governor, clutch packs, latching mechanism and differential cam gear. The flyweight governor responds to differences in wheel speeds. When one wheel is spinning substantially faster than the other, the governor spins rapidly, causing the flyweight governor to open. The flyweight then catches on a latching bracket and the lock-up process begins. During lock-up, a self-energized clutch system causes a cam plate to ramp against a side gear. This ramping action compresses the clutch packs mounted between the side gear and the case. The ramping continues until both wheels

are spinning at the same speed. Both wheels will remain locked (connected) until there is a torque reversal and then the differential goes back to an open condition. There is another flyweight, which responds to absolute speed of the rear axle to disallow the locking function above a specific vehicle speed. A typical example of this type of LSD is shown in Figure 10.10.



Figure 10.10: Example of a Mechanical Locking Differential

Although the system only functions at low vehicle speeds, its ability to remain fully locked without the need of continuous speed difference provides excellent traction performance.

ELECTRONICALLY ACTUATED LSD

Electronically controlled LSDs are externally controlled by an electronic control unit (ECU) and offer the highest level of axle differential control.

Compared to the various passive differential technologies covered in the previous sections of this manual, active differentials offer significant vehicle level benefits. Active systems are externally controlled with access to various sensors (input speed, output speeds and yaw velocity) and an electronic control unit to process these signals and send a signal to the actuation mechanism. Active systems are very versatile and can be integrated with other systems such as

anti-lock braking, traction control, stability control and chassis control for improved vehicle level performance. The system's capability is only limited by the number of sensors used and the control algorithm employed.

There are three types of electrically controlled clutches typically used for limited-slip axle differential applications:

1. Electro-Hydraulic
2. Electro-Motor
3. Electromagnetic

Electro-Hydraulic Type LSD

A typical mechanization of a hydraulic actuated limited-slip axle differential consists of a gerotor type pump, which generates pressure when there is a speed difference across the unit. The hydraulic pressure from this mechanical pump is electronically controlled by a variable flow valve to control the apply pressure to the clutch. The performance of the device can be tuned based on the software algorithms that control the position of the valve, but the available hydraulic pressure must be generated by wheel speed difference. An example of this type of LSD is shown in Figure 10.11.

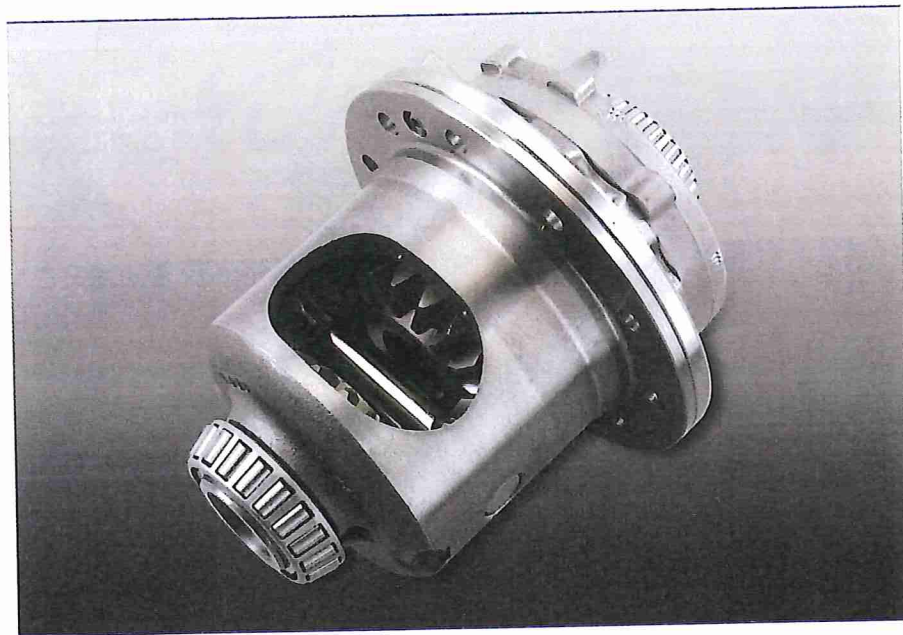


Figure 10.11: Example of an Electro-Hydraulic Type Limited-Slip Axle Differential

Similar hydraulic clutch actuation can be accomplished by using a hydraulic power pack system consisting of an electric motor to drive an oil pump with a pressure accumulator. Such a system can provide hydraulic pressure independent of wheel speed difference.

Electro-Motor Actuated Type LSD

These active devices use a controlled electric motor (e-motor) to directly actuate the clutch. There are two ways:

1. Electric motor driving a cam mechanism
2. Electric motor driving a hydraulic source piston

Mechanical cam actuation consists of the e-motor driving a cam-type mechanism to translate rotational displacement into axial displacement. This can be achieved in several ways. Figure 10.12 shows a system that uses an electric motor driving a reduction gear that then rotates a uni-directional ball cam mechanism, thereby inducing an axial force to compress the clutch pack.

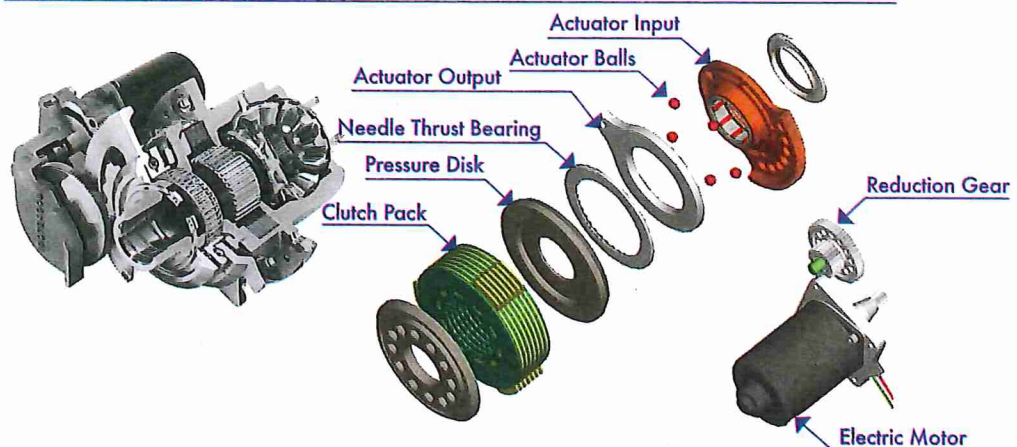


Figure 10.12: Example of Electro-Motor Driven Cam Clutch Actuation for Axle LSD
(Source: Courtesy of GKN Driveline)

Another method to directly actuate a clutch pack using an e-motor can be achieved by using a hydraulic source piston to hydraulically apply the clutch pack. The working principle of this type of LSD application is explained in Chapter 8. An example of this type of actuation system can be seen in Figure 10.13.

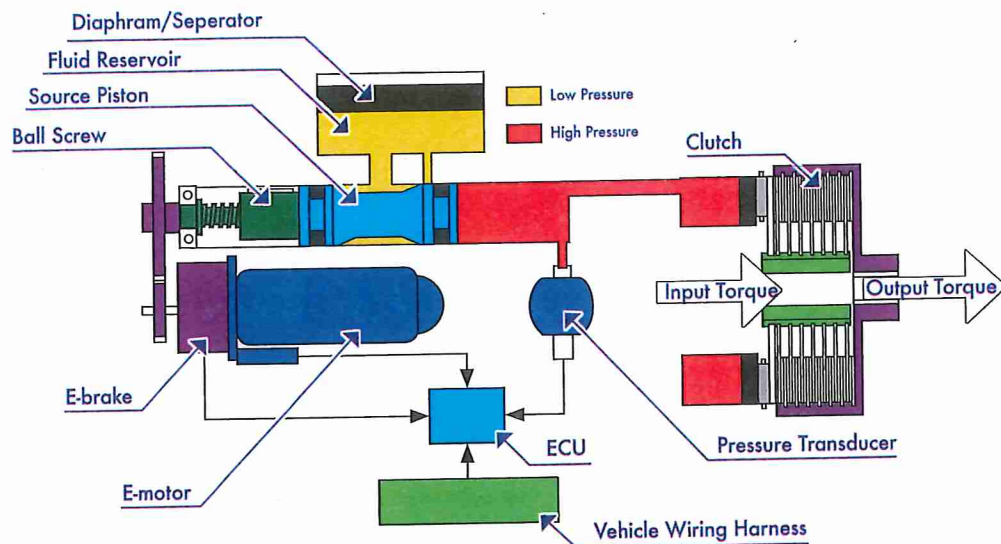


Figure 10.13: Example of Electro-Motor Driving Hydraulic Source Piston

Electromagnetic Actuated LSD

Electromagnetic actuation of a clutch can also be used to provide active LSD control. The working principle of this type of clutch actuation is explained in Chapter 8. An example of this type of LSD application is shown in Figure 10.14.

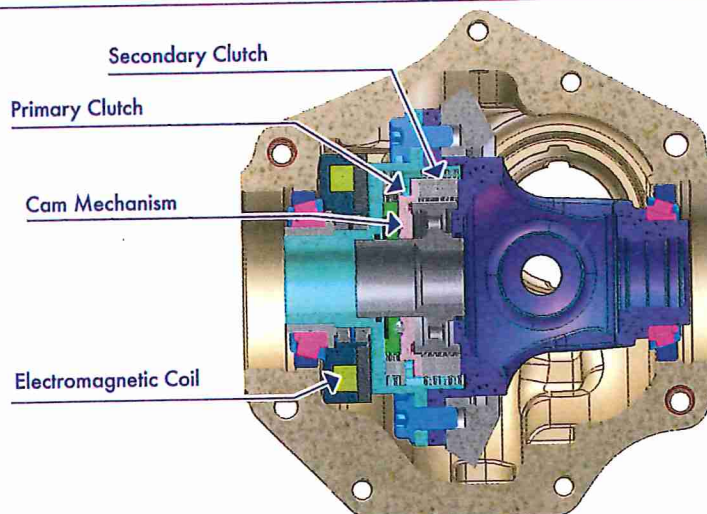


Figure 10.14: Example of Electromagnetic Clutch Actuation for Axle LSD



CHAPTER 11

By David E. Bruder contributing Dave Haselton

VEHICLE DYNAMICS

The dynamic behavior of a vehicle is determined by the properties of the vehicle and by the external forces that act upon it. The vehicle properties include inertias, compliances, tires and aerodynamic configuration, to name a few. The external forces include gravity, road forces, air resistance, and perhaps most significantly, the input of the vehicle's driver. These influences and others combine to determine, among other things, whether a vehicle will smoothly negotiate a given curve, or spin out of control off the road. These dynamics also determine how a vehicle will accelerate, ride and brake. This chapter discusses several ways in which vehicle dynamics can affect all-wheel drive performance, and ways in which all-wheel drive behavior can influence vehicle dynamics.



Cadillac CTS

Tire Behavior

Tires transmit forces to the road surface that enable the vehicle to accelerate, maintain velocity against aerodynamic drag, corner and brake. One of the key things to understand about tires transmitting force to the road is that tires do not transmit force unless they “slip.” In straight-line driving, the tires on the driving axle rotate at a slightly faster speed than would a wheel freely rolling at the same linear velocity (e.g., the wheels of the non-driven axle). As the tire reacts against the road, the tread elements and tire carcass flex like a spring and relax once that portion of the tire leaves the contact patch (see Figures 11.1 and 11.2). The result is a difference between the longitudinal velocity of the tire and the tire contact patch velocity.

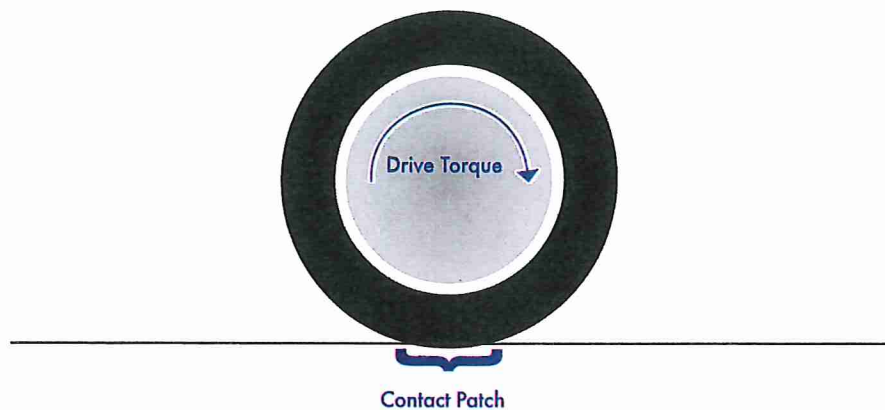


Figure 11.1: Tire Contact Patch

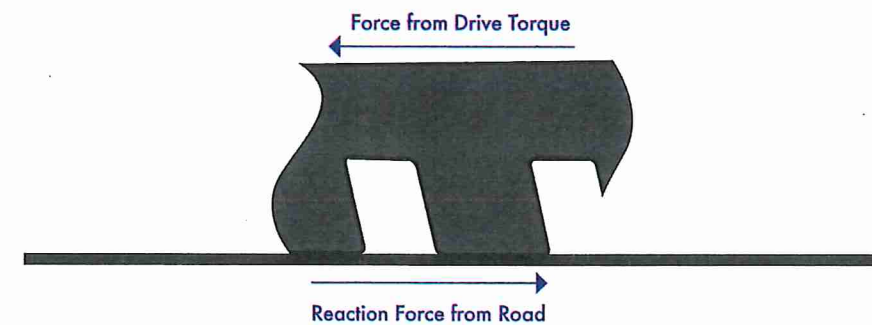


Figure 11.2: Individual Tread Elements in the Contact Patch

There is a similar effect in cornering. This effect is usually quantified in terms of the “slip angle” of the tire. When the vehicle is cornering, the tires must react to lateral forces against the road. Because the tire flexes under this load as the tire material rolls through the contact patch, there is a difference between a tire’s orientation and its direction of travel as shown in Figure 11.3. This difference is called the “slip angle.” When there is little lateral loading, the tire basically rolls in the same direction as its orientation with a slip angle of approximately zero. As lateral force is increased, the tire travels at an angle relative to its heading.

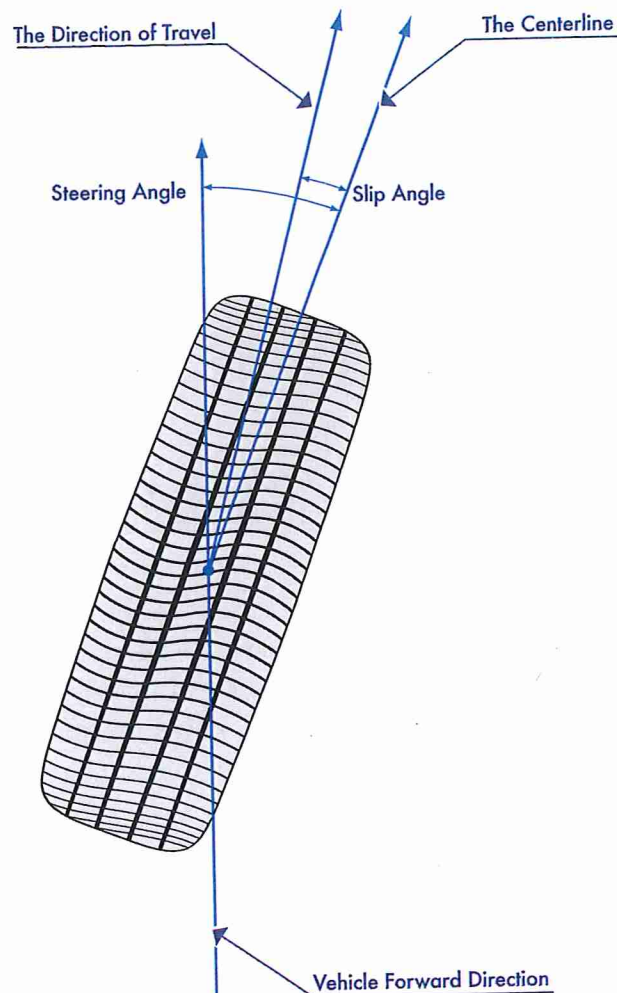


Figure 11.3: Tire Slip Angle



Porsche Cayenne Turbo

Acceleration

When the vehicle accelerates, engine torque is transmitted through the drivetrain to the wheels where the frictional reaction force between tire and road ultimately drive the vehicle. The vehicle dynamic that occurs in acceleration is weight transfer to the rear wheels due to the acceleration of the vehicle mass and the center of gravity height of that mass (see Figure 11.4), as well as suspension behavior. In rear-wheel drive vehicles, the resulting moment increases the tractive capability of the vehicle by increasing the normal load on the driving wheels. In front-wheel drive vehicles, acceleration performance is compromised because the normal load

on the driven front wheels is reduced as acceleration increases. This is one reason why performance enthusiasts generally prefer RWD over FWD for high-powered vehicles. The acceleration potential for a vehicle is limited either by the torque available from the powertrain or the available grip, which is the product of tire/road friction and normal load on the driving wheels (including dynamic weight transfer).

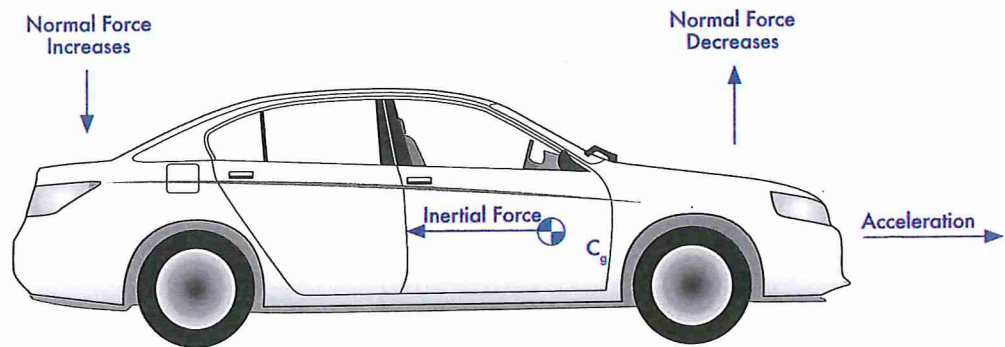


Figure 11.4: Dynamic Weight Transfer During Acceleration

While 2WD vehicles rely on friction available at two wheels, AWD vehicles take advantage of the friction available at all four wheels (both axles) for acceleration. The added friction available in AWD vehicles provides a greater potential acceleration capability compared to 2WD vehicles, although this potential may exceed what the powertrain can provide. Vehicles with fixed front-to-rear torque distribution may not be able to take advantage of all available grip, because the normal load distribution changes as a function of acceleration. Vehicles with active/variable front-to-rear torque distribution are able to more fully utilize the available grip by adapting to the dynamic effects of weight transfer.

Cornering

In cornering, lateral forces are developed at the tire contact patches by forcing them to run at an angle (slip angle) to the tires' direction of travel. Normally, the lateral force increases steeply at small slip angles, peaks at around 5 degrees to 15 degrees, and eventually declines from the peak as slip angle increases further. Additionally, if the tire is generating high levels of longitudinal slip due either to braking or acceleration, its ability to develop cornering or lateral force is diminished. In the case of a locked wheel, no cornering force can be developed at all.

Understeer, oversteer and neutral steer are terms that are used to describe a vehicle's cornering behavior.

Understeer

Understeer is sometimes referred to as "pushing," where the vehicle steers less than expected. This is common in FWD vehicles under heavy acceleration. When understeer occurs, the driver tries to turn and accelerate at the same time and finds that the vehicle makes a larger radius turn than desired. The technical definition of understeer is when the average of the front tire slip angles is greater than the average of the rear tire slip angles.

Oversteer

Oversteer is sometimes referred to as "looseness" or "fish-tailing," where the rear end of the vehicle begins to "come around." This is usually an uncomfortable condition for novice drivers and requires driver training on how to counter-steer (steering in the same direction that the rear of the vehicle is going) to avoid losing control of the vehicle. This condition is common in RWD vehicles during heavy acceleration. In rally driving competitions, vehicles are intentionally placed by their drivers in an oversteer condition so that a high body slip angle is maintained to improve cornering speed. This sustained oversteer is referred to as drifting. The technical definition of oversteer is when the average of the rear tire slip angles is greater than the average of the front tire slip angles.

Neutral Steer

The last cornering term is neutral steer. As might be assumed, a vehicle is said to have neutral steering when front and rear tire slip angles are equal (see Figure 11.5).

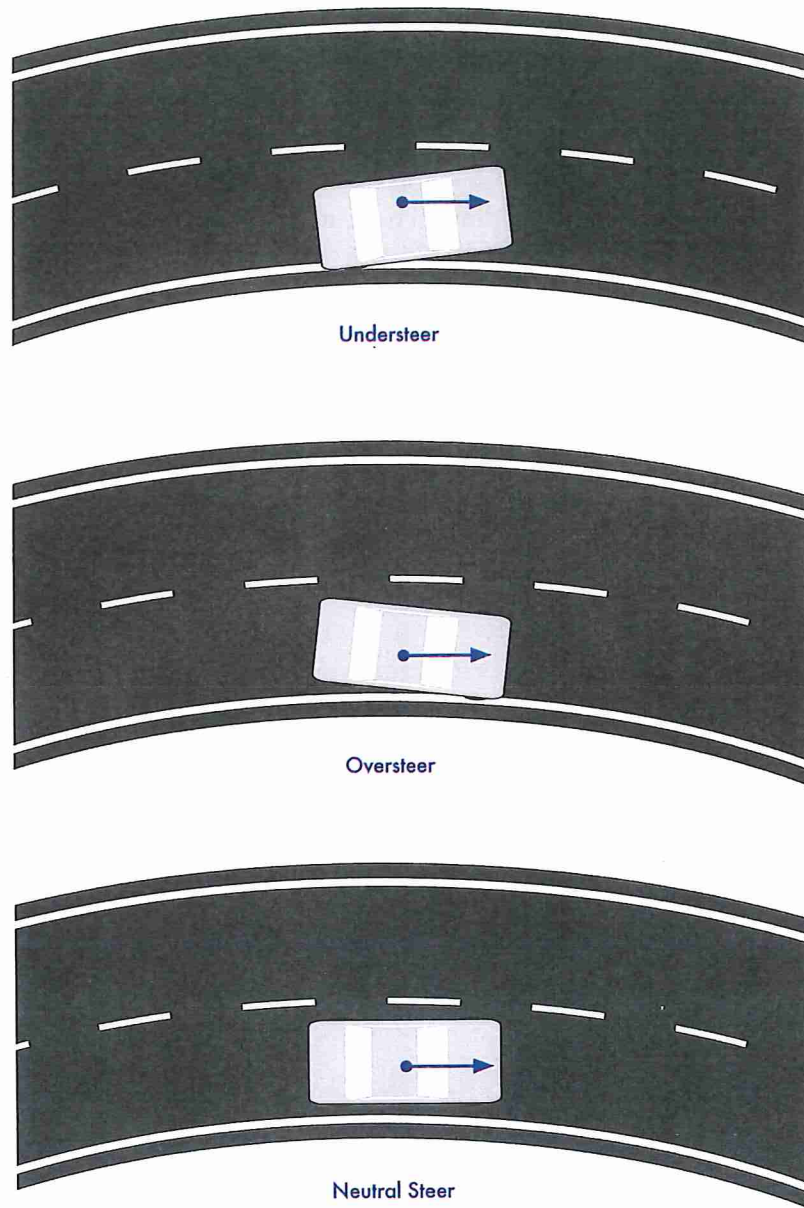


Figure 11.5: Vehicle Cornering Behavior

The effect the powertrain has on cornering is this: driving torque generates longitudinal slip on the tire, which decreases cornering capability. When driving torque is added during cornering, the slip angle of the driven wheels increases. If a tire is already near its peak cornering force, its lateral grip will be reduced by the addition of driving (longitudinal) force. This is why FWD vehicles tend to understeer and RWD vehicles tend to oversteer when driving torque is applied.

In AWD vehicles, the forces involved in accelerating the vehicle are spread over four wheels instead of just two. The implication of this is that there is some reduction of lateral force capability at both axles rather than just the front or rear alone. This reduction in force leads to more neutral on-throttle handling. There are subtleties in how different types of AWD affect cornering, which are described below.

Part-time systems are generally only engaged for off-road situations, but are sometimes used on public roads when conditions are poor. The part-time AWD system creates a kinematic constraint on the driveline that forces the front and rear average wheel speeds to be the same. This creates some interesting cornering behavior. At the initiation of a turn, the front wheels naturally want to turn faster than the rears because they traverse a larger turning radius. Figure 11.6 illustrates how each wheel travels through a different turn radius when the vehicle is cornering. Vehicle steering systems are designed so that the front wheels turn at slightly different angles to accommodate this effect.

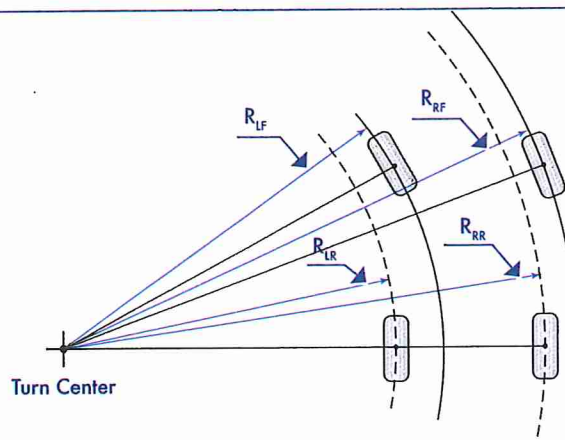


Figure 11.6: Individual Wheel Cornering Radii—each wheel speed is proportional to its cornering radius (Source: BorgWarner and Joseph Palazzolo)

This initially results in braking forces at the front axle and driving forces at the rear due to the locked transfer case (the front wheels are forced to turn slower than they want to and the rears are forced to turn faster than they want to). This usually results in understeering at low throttle levels due to the increased longitudinal slip on the front wheels. However, as throttle is increased, the vehicle can tend to oversteer because of excessive longitudinal slip at the rear axle compared to the front. The front and rear slip do not balance until the rear wheels are traveling through the same cornering radius as the front wheels. This tendency increases with smaller radius turns and higher acceleration. Of course, this effect only occurs as the limits of grip are approached, but a driver will experience it frequently in snowy conditions, for example.

An AWD vehicle with center differential is designed to be driven on public roads, differing from the part-time system in that it allows the front and rear axles to run at different speeds (as is required for smooth cornering). The center differential is so named because it allows the front and rear axle speeds to "differentiate." These vehicles are generally well-behaved and consistent in cornering since they do not suffer the kinematic constraint of vehicles with the part-time system. Another key characteristic of the center differential AWD vehicle is that it is set up to mechanically proportion a fixed fraction of driving torque between front and rear. When this "torque split" is matched to the vehicle weight distribution (for example, 40%/60% front-to-rear torque distribution and 40%/60% front-to-rear weight distribution), on-throttle behavior is fairly neutral. When there is less front weight distribution than front torque distribution, the vehicle exhibits more understeer in on-throttle cornering.

Such understeering may be desired for stability, but can result in an unsatisfying driving experience because the vehicle will feel heavy and unresponsive to cornering inputs. Variations in vehicle loading affect the weight distribution, but because the torque split is fixed by the differential design, the torque split will not be "matched" for all loads. For instance, sometimes vehicles that are intended to perform towing are set up with rear torque bias, such as 35/65 front/rear, to accommodate the additional load on the rear axle when towing. This rear torque bias results in a compromise, since tuning the torque distribution for towing means that when the vehicle is not towing it will have excess torque distribution to the rear relative to its weight

distribution. This compromise condition predictably results in the vehicle's tendency to oversteer on throttle.

Active on-demand AWD systems have an advantage over both part-time and center-differential systems in that they allow both inter-axle differentiation and variable torque split. These systems detect turning and estimate individual wheel slips, so that torque distribution can match actual operating conditions. In terms of torque distribution, improper torque distribution results in front and rear wheel slips which are out of balance. When driving slips are balanced, torque distribution is balanced and proportional to weight distribution. In terms of differentiation, active on-demand AWD systems must strike a balance between transferring torque and allowing differentiation. When an active on-demand system is operating at sufficient torque capacity to lock the clutch, it is just like a part-time system in lock mode, with the same kinematic constraint on wheel speeds. In practice, torque transfer and inter-axle differentiation are balanced in active on-demand systems by appropriate control algorithms and tuning.

Braking

In braking, wheel brakes are activated under hydraulic pressure, and braking torque is applied to all four wheels. As the torque is applied, longitudinal tire slip is developed. This slip works the same way as when driving forces are applied.

Braking force typically peaks between 10% to 20% slip (when the wheel is rotating 10% slower than it would if free rolling) on pavement, as shown in Figure 11.7. Slips below the peak force level are considered to be the stable region of tire slip because the slip is easy to modulate. Tire slip levels above peak are considered unstable because the slip is difficult to modulate and quickly proceeds to the locked condition. This is because the peak torque exceeds that required to lock the wheel. An exception to such an occurrence is when a vehicle is driven over deformable surfaces, such as dirt or gravel, where the braking force continues to climb with slip and peak force occurring at locked condition.

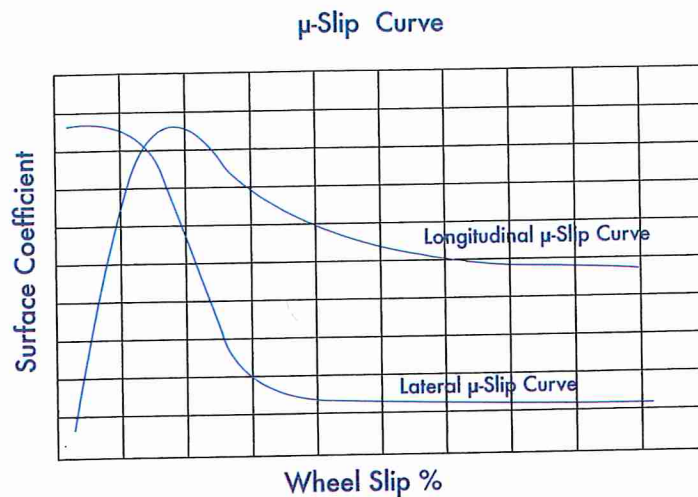


Figure 11.7: Lateral and Longitudinal μ -Slip Curve. (Source: Delphi-Beyer, Krueger, Sonnenberg, SAE Paper 2002-01-1217)

One of the objectives of braking systems is to balance the braking forces front-to-rear over the range of vehicle loading conditions, and to maintain a front-biased condition. This means the brake force distribution must always be more front-biased than the vehicle weight distribution. This is the case for all vehicles. If at any point the brake system becomes rear-biased, the vehicle will become unstable. To remain front-biased and accommodate weight transfer, a proportioning valve that progressively limits rear brake pressure to maintain front-biased braking must be specified.

It is becoming increasingly common to proportion rear brake pressure using the electronic proportioning via the anti-lock braking system. Electronic proportioning monitors wheel slips during braking, adjusting rear brake pressure to keep front and rear slips balanced (slightly more slip in front compared to rear). This proportioning action is similar to what an active on-demand AWD system does to balance drive torque distribution. One may wonder why a driver would

tolerate oversteer-inducing drivetrains (like the center differential) but not oversteering brake systems. The reason is that when a driver needs to stop, he or she needs to stop and cannot just let off the brake pedal to stabilize the vehicle. If the driver's vehicle has on-throttle oversteer, then the driver can just decrease throttle to reduce the oversteer.

Friction Circle Concept

There is a useful concept that ties together acceleration, braking and cornering nicely by way of understanding tire force capability at the contact patch: it's called the "friction circle."¹ The idea behind the friction circle is that the tire has only a certain tractive capability in any given situation. This tractive capability is determined by the available friction between the tire and road and the normal load on the tire. This capability envelope is roughly represented by a circle, hence the name friction circle.

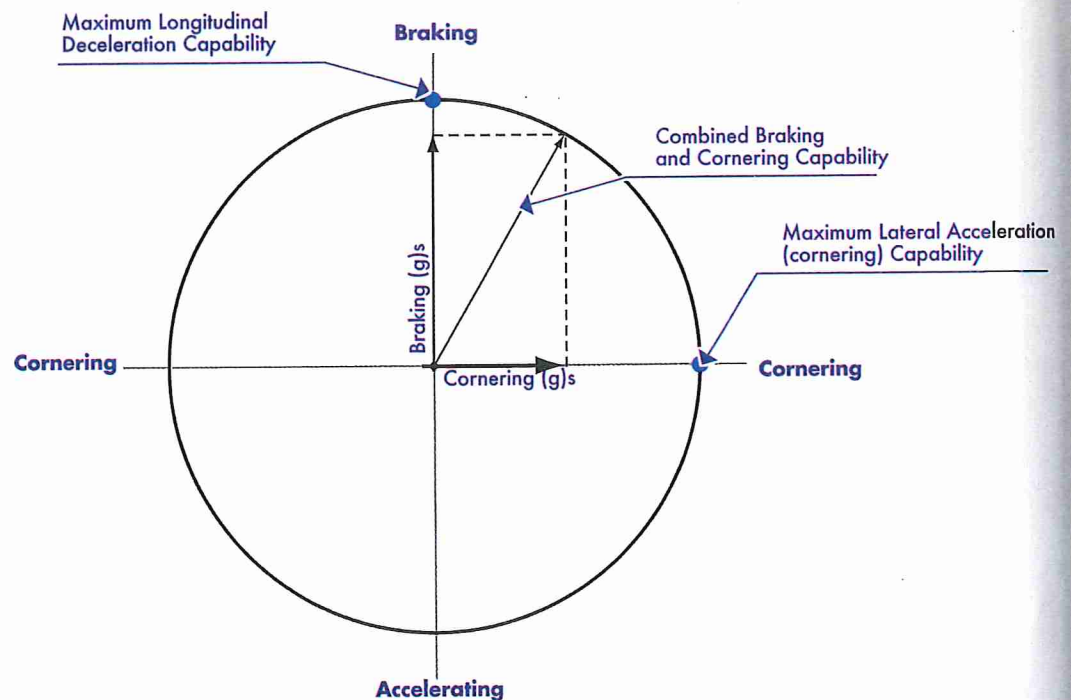


Figure 11.8: Friction Circle

¹ Joseph Palazzolo, "Fundamentals of All-Wheel Drive Systems" (1997), 16–17.

A tire's tractive capability is defined by the friction circle as the resultant of its lateral and longitudinal force vectors. Thus cornering is limited or non-existent under maximum braking or acceleration and maximum cornering is achieved under steady speed conditions.

BRAKE CONTROL SYSTEMS

Brake control systems started to become popular in the 1980s and have become ubiquitous in the 21st century—beginning with anti-lock braking systems (ABS), proceeding to traction control and advancing to electronic stability control (ESC). ABS is a microprocessor-controlled, electro-hydraulic modulator that has the ability to isolate pressure input from the brake master cylinder and regulate it individually to each wheel.

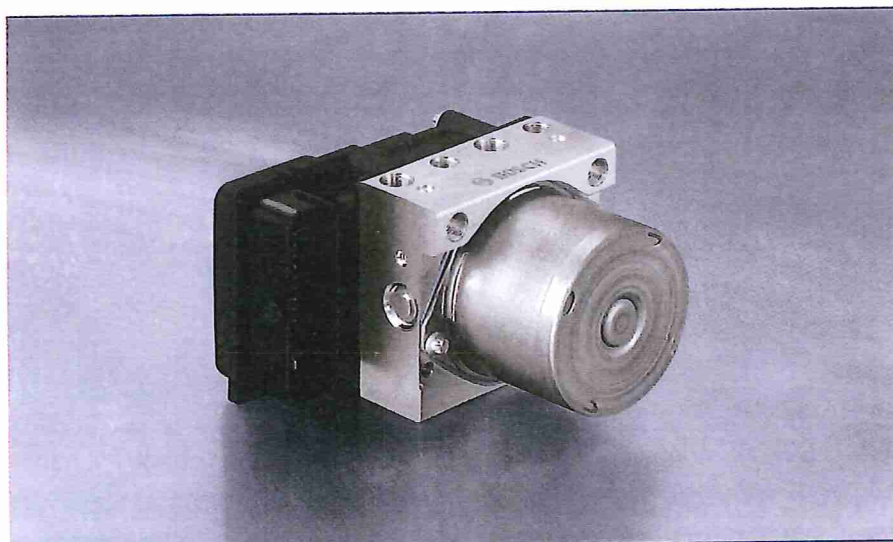


Figure 11.9: ABS Electro-Hydraulic Modulator (Source: Courtesy of Bosch)

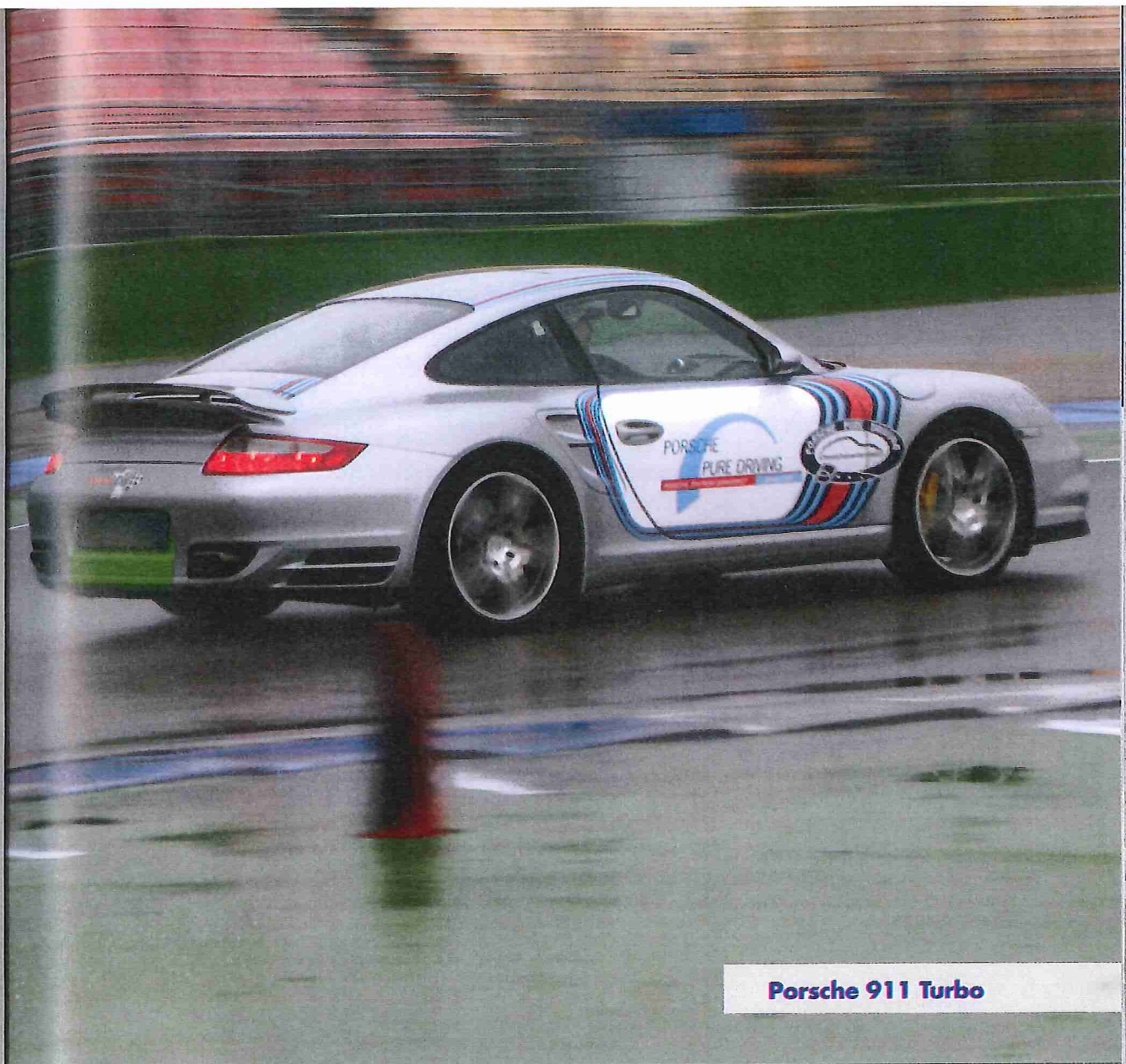
An example of an ABS modulator is shown in Figure 11.9. Actually, ABS, Traction Control (TC) and Electronic Stability Control (ESC) for hydraulic braking systems are close cousins in that they are all electro-hydraulic modulators, each with progressively more valves and functionality. ABS modulators can only reduce individual brake pressures relative to the driver's input to the brake master cylinder. TC modulators add the ability to apply pressure to the brakes on the

driven axle without pressure input from the brake master cylinder (this serves to brake a wheel that has lost grip and transfer torque across the axle differential to the other side). ESC modulators can apply pressure to all four brakes independently without any input from the brake master cylinder (this allows application of brake forces to stabilize the vehicle).

Anti-Lock Braking Systems

The mission of ABS is to regulate wheel slip during braking, to keep vehicle deceleration near its peak capability while maintaining vehicle steering and stability. If a front wheel locks, steering is impaired. If a rear wheel locks, vehicle stability is affected. ABS does not become “active” until predetermined slip thresholds are crossed—usually during heavy or panicked braking maneuvers. ABS systems also usually take over the job previously performed by hydraulic proportioning valves to limit pressure to the rear brakes. This keeps braking forces in balance front-to-rear as deceleration causes increased weight distribution to the front wheels.

When the ABS system is regulating slip, it must regulate against a target. This target is referred to as the reference velocity. Reference velocity calculation requires some complex logic to make sure it accurately reflects vehicle velocity. If all four wheels are in deep slip, reference velocity can be corrupted (artificially low), because it is determined by the wheel speeds. For this reason, pressure is periodically reduced to allow one or more wheels to return to true vehicle velocity. Accurate reference velocity enables accurate wheel slip estimation and control for optimal braking performance. This leads to an important interaction between AWD and ABS systems. When the AWD system is coupling front and rear axles, the ABS system may not be able to bring one of the wheels back up to vehicle speed due to the driveline coupling. This can result in a condition known in the braking community as “reference velocity sneak-down.” In this condition, deceleration on ice may seem to the ABS as a regular μ stop, since all four wheels decelerate together. Reference velocity sneak-down can be avoided, either by adding extra sensing, such as longitudinal acceleration (for an independent reference velocity check) or by allowing the ABS to temporarily reduce AWD coupling. Vehicle network communications



Porsche 911 Turbo

make the latter solution convenient. When the ABS system is actively controlling brake pressures, it sends an “ABS-active” signal to the AWD system and requests a certain AWD coupling level (often zero) until ABS activation is completed.

Traction Control

The purpose of traction control (TC) is to regulate slip on drive wheels during acceleration. This is generally accomplished by a combination of brake intervention and engine torque reduction. By braking one or both drive wheels, wheel spin-up can be quickly contained. Engine torque reduction can be employed to reduce the brake torque required

to control slip. But it is a secondary control intervention, because engine torque is slower to respond than the brakes.

The benefits of traction control are analogous to those of ABS: achieve optimal acceleration, maintain steerability and prevent excessive on-throttle oversteer or understeer. A trained driver can usually accelerate faster with the TC system turned off, but for most drivers, leaving the system on yields a better result. When AWD is combined with traction control, the reference velocity problem arises again. With 2WD TC, the non-driven wheels provide almost perfect reference velocity with which the driven wheel speeds can be compared. AWD disturbs this relationship by transferring torque to both axles. The solutions to these disturbances are a little different from the solutions for ABS. One solution is to avoid any front-to-rear slip control via TC. This lets AWD be in charge of front-to-rear slip, puts TC in charge of cross-axle slip and eliminates the reference velocity problem.

Electronic Stability Control

Electronic stability control (ESC) takes traction control one step further by including the capability for four-wheel independent brake actuation. ESC also has additional sensor capability that may not be present with ABS or TC, including steering wheel angle, yaw rate and lateral acceleration. Such a combination of sensors gives the system the ability to compare estimated vehicle body motion states with expected values based on the driver's steering input. The system can then use brake application at individual wheels to influence body motion to conform to the driver's steering input and to keep the vehicle heading and velocity vectors more or less aligned. For example, ESC can mitigate oversteer or understeer by braking either the outside or inside wheel(s), thereby inducing a corrective yaw moment on the vehicle.

Active AWD must typically be disabled or put in a fixed, predetermined state for effective ESC operation. To accomplish this, ESC sends a message to AWD requesting a temporary change in AWD torque coupling while ESC is actively stabilizing the vehicle. This temporary change is necessary because the AWD system transfers torque through the driveline. ESC braking forces at one wheel are reacted through the driveline to the other wheels when AWD is engaged. If the AWD

system is active, ESC is unable to predict the torque coupling, and the reacted braking forces produce incorrect yaw moments on the vehicle, thus diluting or canceling the intended ESC effect.

Lightweight Drivelines

A growing trend in AWD applications is to undersize driveline components relative to skid torque in order to save cost and weight. This generally means that the AWD coupling must perform the function of “torque fuse” to prevent damage to other driveline components. When drivelines are designed to handle full skid torque, as they are in off-road-oriented vehicles, the AWD coupling can protect itself from excessive slip and consequent thermal overload by applying increasing clamp load.

In the lightweight driveline however, the coupling must not exceed its prescribed protection torque limit. Without electronic control of coupling differential speed, the coupling is subject to thermal overheating and damage. This damage occurs when coupling torque is at its upper limit but slip is unregulated due to loss of traction and excess engine torque. As discussed earlier in this chapter, most TC and ESC controllers have the ability to interface with the powertrain to request reduced engine torque and protect the AWD coupling from excessive power dissipation. For this reason, it is always best practice to combine lightweight AWD systems with coupling differential speed management via engine torque reduction.


Lightweight AWD systems give up some tractive and dynamics capabilities due to the torque limit on the secondary axle. Tractive loss shows up in acceleration and gradeability, particularly in conditions where the primary axle suffers a loss of grip and the torque-limited secondary axle is providing main vehicle propulsion. Vehicle dynamics are compromised when the coupling is unable to control slip due to excess engine output, resulting in understeering or oversteering (depending on whether the vehicle is primarily FWD or RWD, respectively). The understeering or oversteering tendency is mitigated by engine torque reduction, while the accompanying reduction in acceleration is part of the lightweight driveline trade-off.



Chrysler 300

DRIVELINE MASS AND LOSS EFFECTS

Driveline rightsizing or downsizing refers to the process of designing vehicle drivelines below the skid torque requirements or the maximum torque capacity that the wheels can deliver. Historically, all-wheel drive drivelines were typically designed to be skid torque capable, thus assuring that driveline components would not fail, even under extreme conditions. However, in some cases, limiting driveline torque levels was necessary to protect components. An active on-demand all-wheel drive system with fully integrated controls offering both thermal compensation and protection logic enables rightsizing. These systems assure accurate and responsive



torque management. It should be noted that because customer usage also affects the driveline lifetime duty cycle, it is equally important for the designers of AWD systems to consider the driver's traction and mobility expectations.

Several factors—such as component torque limitations, intentional driveline sizing in line with customer usage profiles and sizing to meet extreme off-road conditions—account for the differences in torque capacity. The more accurate the driveline torque control, the greater the opportunity for the most efficient component sizing and mass—thus further improving fuel economy. However, careful consideration must also be taken by the designer to protect the active all-wheel drive coupling from excessive heat.

Another method to improve fuel economy is to reduce the power loss or conversely increase driveline efficiency. Driveline systems (including the transmission) are not the worst offenders of power loss; they account for only 5.6% of vehicle power losses. Because all-wheel drive systems may contribute up to 2% of this total, however, the AWD technology can still be improved for better fuel economy.

The typical transfer case for a rear-wheel drive based all-wheel drive system offers opportunities to reduce system parasitic losses. For example, the lubrication pump, drive system (chain or gear) and clutch drag are the largest contributors to the losses related to a transfer case in a RWD-based AWD system. The performance of each of these factors can be improved by the AWD designer. Drive system losses can be reduced using oil sump management techniques, such as a chain guard, to reduce oil plunging losses. Clutch drag can be reduced using different approaches to driveline disconnects and clutch system designs. Pump-related losses can be reduced by relocating the gerotor pump off the main shaft. In this approach, the pump design no longer depends on the diameter of the shaft and can be appropriately downsized to improve efficiency.

In addition to the transfer case, the propshafts and halfshafts can also be optimized to reduce parasitic losses. There are new technologies available to the system designer that address constant velocity joints to reduce the joint parasitic losses. Combinations of new joint geometry and grease have shown a reduction in joint losses in excess of 50%. Other designers have found that reducing the operating angles of the joints will also reduce the overall losses. If the joint

operating angle can be reduced to 0.5 degree, then a traditional style joint can possibly be replaced with a flex coupling style joint to further reduce parasitic loss.

The front and rear axles of a typical RWD system also lend themselves to further parasitic loss reductions. One major contributor to parasitic loss is the hypoid offset. The smaller this offset becomes the more efficient the axle becomes. Optimizing the hypoid gear tooth geometry for efficiency will reduce these losses even further. Bearing optimization is possible and some designers have even replaced the traditional preloaded tapered bearings with tandem ball bearings to show improvements. Other areas of consideration are the optimization of the lubricant used, fill level and seals. When adjusted, these areas can result in improvements in the hypoid gear drive systems. These concepts apply to any gear-driven system and therefore can be used in the front-wheel drive based all-wheel drive system power transfer unit as well.

AWD PRODUCT TRENDS

All-wheel drive systems have become quite common in hybrid electric vehicles (HEVs). These systems, ranging from electric secondary axles to conventional all-wheel drive systems, are applied to either FWD- or RWD-based AWD architectures. Forecasters expect the hybrid market will continue to grow and that the all-wheel drive demand for such vehicles will grow along with it. Expected AWD product trends include compact power transfer units (PTU) and transfer cases to aid in driveline rightsizing; compact on-demand all-wheel drive couplings and torque management controls; and torque vectoring solutions that contribute to active safety and handling performance.

One example of this latter trend is the torque vectoring systems that shift torque from right to left and can be used in either driven or non-driven axles. These systems typically involve the use of a combination of gears which, when actuated by a friction clutch, take torque from one side and add that torque to the opposite side to improve the vehicle's cornering ability. The clutch may be actuated by an electro-hydraulic, electromagnetic or electro-mechanical system as in the BMW X6 (see Figure 12.2). Mitsubishi was the first company to use this type of system in 1996. More recently Honda entered the market

with their version of the system: the SH-AWD. These systems add some weight and rotational losses that result in some losses in fuel economy. As such, these systems have thus far been limited to the high performance sport vehicles.

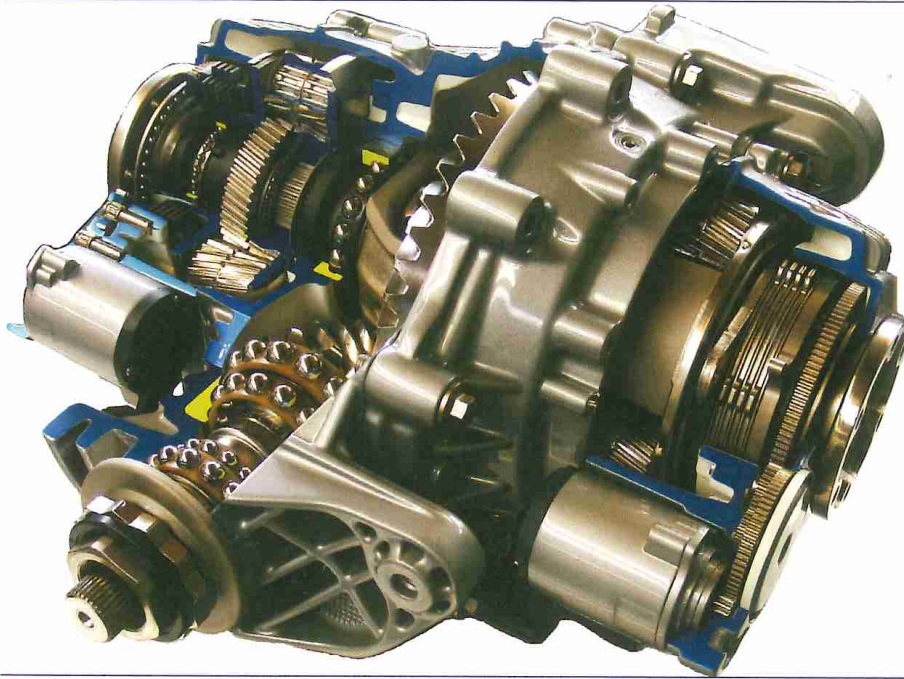


Figure 12.2: BMW X6 Torque Vectoring Axle with Tandem Balls (Source: Courtesy of Joseph Palazzolo/Schaeffler Group)

The next step in the evolution of torque management is the management of torque to all four tires simultaneously, resulting in further optimization of vehicle handling. Although torque-vectoring axles can be used in two-wheel drive vehicles, these axles are typically used in AWD vehicle applications (like the Acura RL, the Audi A5 and the BMW X6) to achieve maximum benefit.

In summary, today's driveline designers must reduce mass and power loss to increase fuel economy. Active on-demand all-wheel drive systems can help the designer achieve these goals now and in the future. Through driveline rightsizing, active on-demand all-wheel drive systems can improve fuel economy and contribute directly to vehicle safety.

ALL-WHEEL DRIVE

All-wheel drive has been inextricably linked with the automobile since the early 1900s. Over the past 25 years, the automotive industry has witnessed tremendous growth in applications of and demand for vehicles with all-wheel drive systems. In fact, worldwide demand for all-wheel drive vehicles in the developing regions of the world is expected to exceed 12 million units by 2015.

Early all-wheel drive systems were used primarily in rear-wheel drive vehicles to improve off-road traction, mobility and ground speed control. Consumer demand for these same improvements in on-road vehicles led to the adoption of all-wheel drive systems and to the integration of these systems with other driveline and chassis systems. Today, drivers seeking increased safety and security have prompted manufacturers to offer all-wheel drive systems in vehicles that might never be driven off-road or in rugged terrain.

Within these pages, outside contributors and engineers from BorgWarner—a leading developer and manufacturer of all-wheel drive systems—explore the history, advantages and future of the all-wheel drive technology. This is a practical manual written for automotive engineers by automotive engineers who spend their days discussing, designing and overseeing the production of the world's most popular all-wheel drive systems.

For engineers, students and auto enthusiasts eager to learn more about all-wheel drive, this book is not to be missed!



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