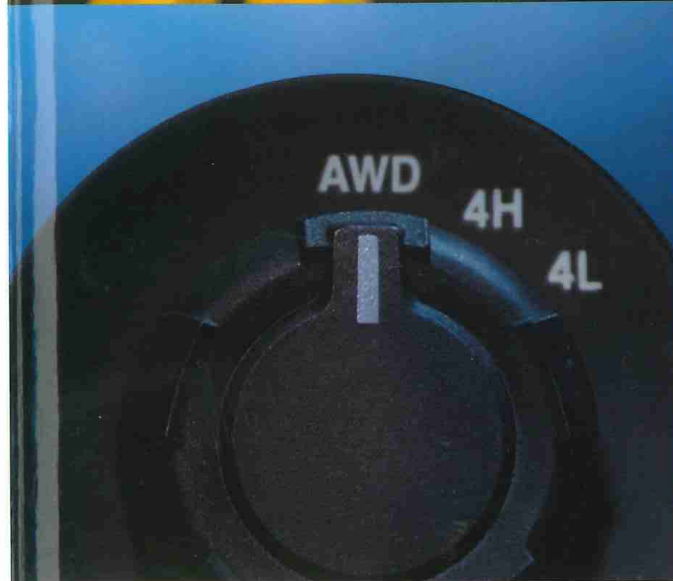
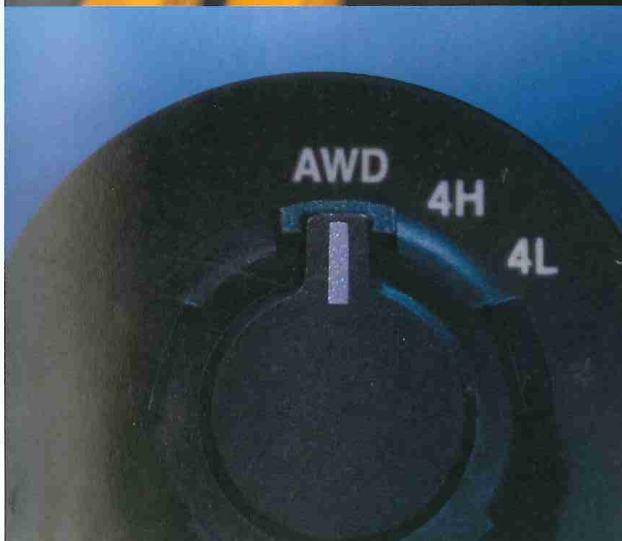
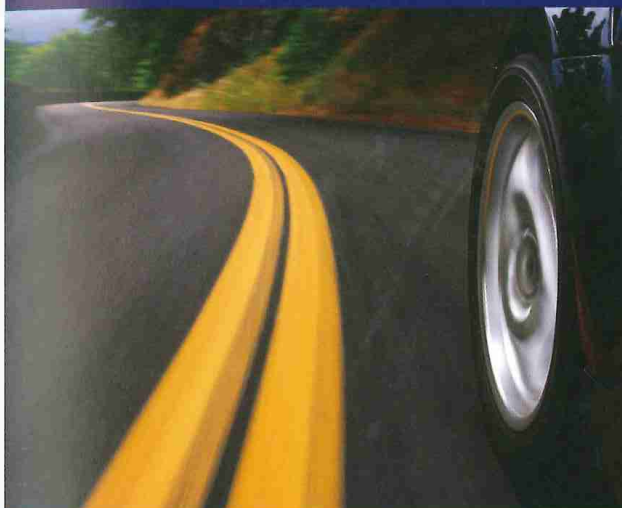


All-Wheel Drive Technology Inspiring Confidence



From a Global Leader in Drivetrain Technology

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 **BorgWarner**
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A Global Leader in Drivetrain Technology

BorgWarner offers a complete line of transfer cases, AWD couplings, electronic limited-slip differentials, torque vectoring axles and hybrid/electric vehicle drive systems. As a leader in drivetrain technology, BorgWarner has provided over 8.4 million active all-wheel drive systems and over 5.5 million electronic control units for the world's automotive Original Equipment Manufacturers (OEMs). Our active, on-demand systems provide drivers with more traction, better handling, increased safety, uncompromised fuel efficiency and—total confidence.



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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.

Global All-Wheel Drive Production (1990 to 2004)

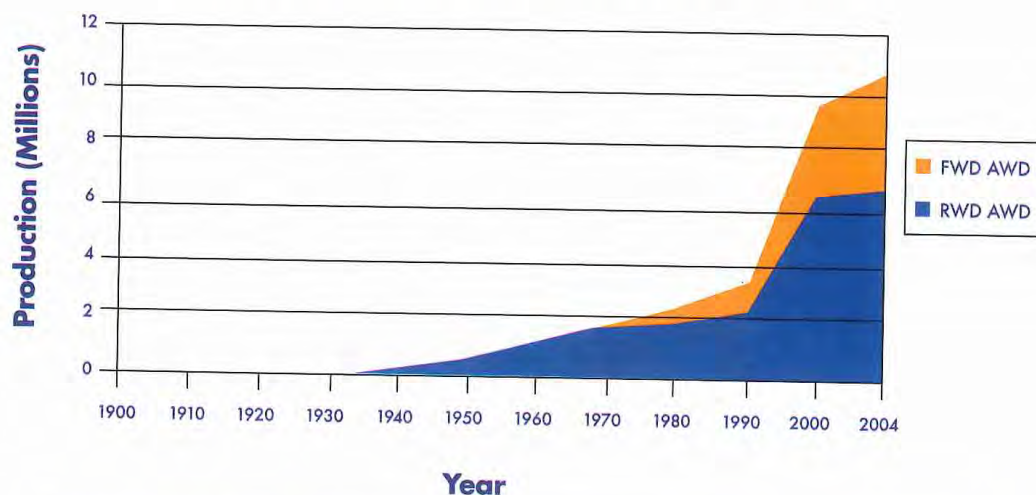


Figure 1.2: Early All-Wheel Drive Market (Source: BorgWarner, CSM, Global Insight, Drucker Research)

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 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.

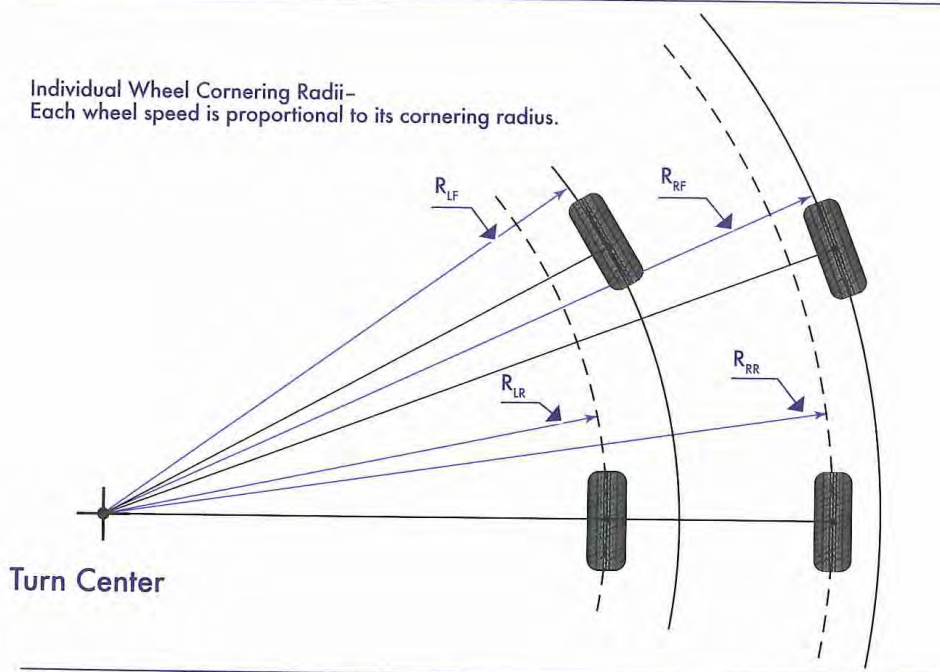


Figure 4.1: Wheel Speeds of RWD Vehicle in a Turn (Source: BorgWarner and Joseph Palazzolo)

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.

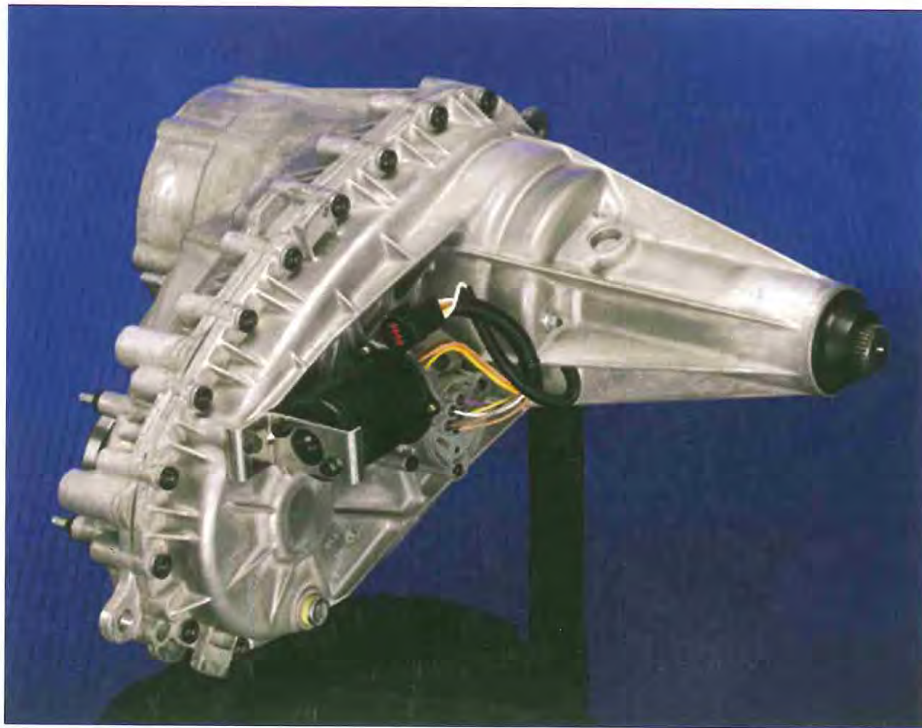


Figure 4.2: BorgWarner 44-16 Transfer Case Featured on the Ford Expedition and Lincoln Navigator

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



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.

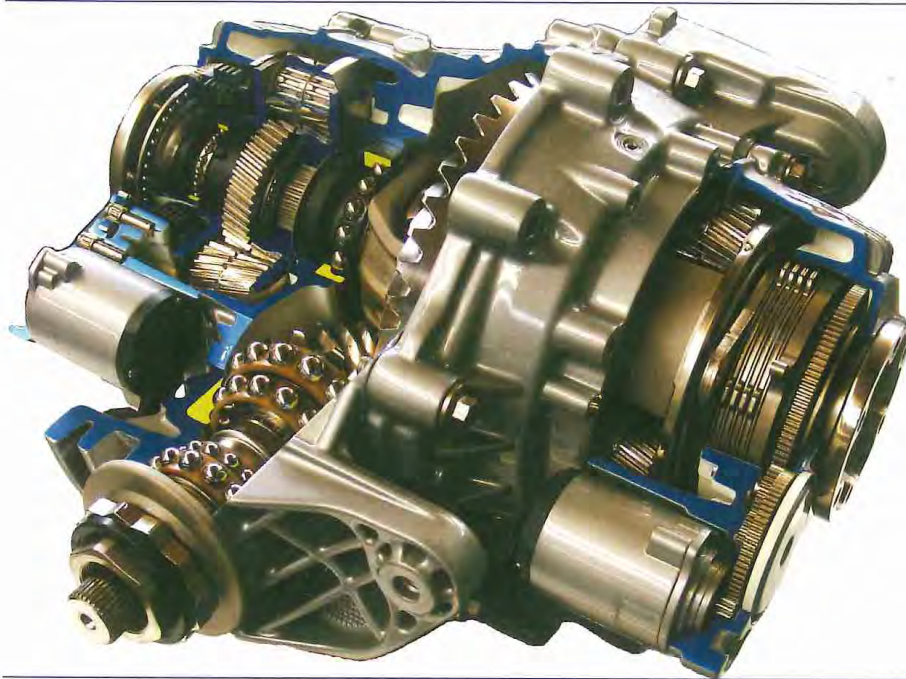


Figure 12.2: BMW X6 Torque Vectoring Axle with Tandem Balls (Source: Courtesy of Joseph Palazzolo/Schaeffler Group)

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!