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*Research Article*

# Four-Wheel Drive System: Architecture, Basic Vehicle Dynamics and Traction

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***Abstract***

*Technology has been developing at a very tremendous pace to improve the safety and comfort of the people and when it comes to luxury and comfort, automobiles section is one of the common topic of interest, the most trending among this section is the "Four Wheel Drive (4WD) system" which has become more advanced and sophisticated with time. It has become an essential and appealing part of automobiles in today's era. This system has made the vehicles more secure, both off-road and on-road, enhanced traction of the wheels and power delivery of the engine. With the manipulation in the fundamental structure of a 4WD, various other 4WD options have become available, suiting different types of lifestyle and environment. This paper attempts to explain the different types of 4WD system, their basic structure, basic vehicle dynamics affecting the traction control system and provide a conclusion on various philosophies that the 4WD system adhere.*

***Keywords:*** *Four Wheel Drive, Two Wheel Drive, All Wheel Drive, Traction.*

## Introduction

The transmission of energy with least losses has always been a major interest and a problem to overcome and hence with the series of advancements we now have the following transmission system described below:

**2WD**: In 2WD(Two Wheel Drive Mode), typically used in sedans and hatchbacks, only one axle(out of the two) is powered by the vehicle, that is the torque is only split between the two wheels. This can be either used as a RWD (Rear Wheel Drive) or a FWD (Front Wheel Drive) based on the position of the engine, vehicle dynamics, fuel efficiency and weight distribution of the automobile. The torque split ratio between the two axles is 0:100 as only one axle is powered and the other axle is a 'dead axle'.

**Part Time 4WD**: Part Time 4WD is basically a 2WD but is equipped with a "Transfer Case". On standard conditions the vehicle runs on two wheels but also has an option to engage the front two wheels by locking the hubs on the front wheels. The transfer Case has a second gear lever and locking hubs on the wheels attached to the front axle. The power is delivered to the front wheels through the differential present at the front axle. There is absence of centre differential which means that both the axles rotate at same speed making 4WD unsuitable for hard surfaces like bitumen which can lead to "transmission wind-up". The ratio of the torque to each wheel depends upon the traction of the wheel with the surface it's being driven on as well as the road conditions when the 4WD is engaged. The vehicle also has an option to select "High-Range 4WD" which lets the vehicle to power all four wheels with same speed ratio as that of 2WD and "Low-Range 4WD" which decreases the speed ratio leading to the increase in RPMs(Rotation Per Minute- of the combustion cycle in the Internal Combustion(IC) engine) generating more torque in less speed (http://www.outbackcrossing.com.au/FourWheelDrive/Different_Types_of_4WD.shtml).

**Full Time 4WD**: A Full Time 4WD is the system in which both the axles are powering the vehicle at all times. There is no selection of 2WD available in such automobiles. A Full Time 4WD is equipped with a centre differential (inter-axial differential) which allows the all the four wheels to rotate at different speeds, avoiding the transmission wind-up.(http://www.outbackcrossing.com.au/FourWheelDrive/Different_Types_of_4WD.shtml) The inter-axial differentials allows slippage between the two axles whereas the differentials preset at either end allow the slippage between each wheel. The slippage occurs when the driving driveshaft becomes faster than the driven driveshaft (http://www.awdwiki.com/en/all wheel drive explained/#selectable_all_wheel_drive) If the centre differential is "locked" the transmission will work as a Part Time 4WD.

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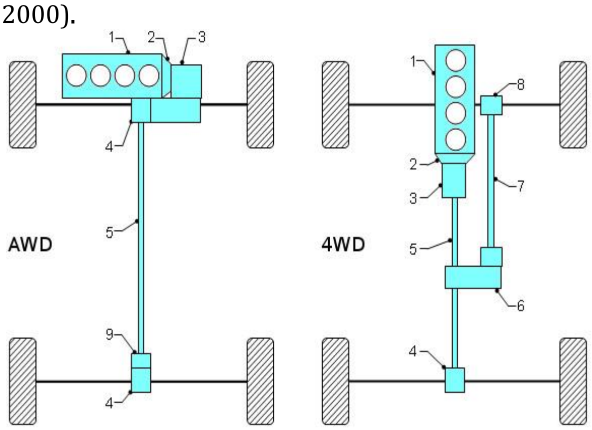
**All Wheel Drive (AWD)**: AWD systems are often confused with other 4WD systems but have a completely different proposition .An AWD system also has an inter-axial differential but does not have the ability to lock the inter-axial differential, restricting it to perform like a Part Time 4WD system. An AWD system can be made to operate in various ways depending upon the preference on the manufacturer.(http://www.outbackcrossing.com.au/FourWheelDrive/Different_Types_of_4WD.shtml) In an AWD system, with the presence of 'On-Demand Mode' the vehicle can operate in 2WD mode and engage the AWD automatically when there is wheel slippage and as soon as it is eliminated, it goes back to the 2WD mode. This is done by using a multi-plate hydraulic clutch, viscous coupling or any other device which can engage the other driveshaft (http://www.outbackcrossing.com.au/FourWheelDrive/Different_Types_of_4WD.html)(http://www.fourwheeler.com/how-to/68958-how-transfer-cases-work)

4x4 Transmissions in automobiles are being used for various purposes since early 1900s. This system has now evolved to become more sophisticated from basic mechanical devices with the integration of technology over the years. 4x4 transmissions are mostly available in heavy duty vehicles such as pickup trucks and SUVs which are often used off-road and on rugged terrains. In a nutshell, the four-wheel drive(4WD) helps in providing better mobility of the vehicle that is, providing traction to all the four wheels of the vehicle. With the incorporation of technology over the years, the basic 4WD system which was once cumbersome to use and highly required driver capabilities, has now become more user-friendly. It has enhanced the safety of the vehicles on-road, provided more traction control and increased the practicality of an automobile. The typical 4WD system has given birth to other advanced drive systems such as AWD (All Wheel Drive) which follow the same basic principles of a 4WD but differ in their mechanisms and provide more driving options. The advancement of the basic 4WD has now also helped the automakers to incorporate the 4WD as an additional feature in other smaller transmissions such as FWD(Front Wheel Drive) and RWD(Rear Wheel Drive), used in vehicles which are often made fuel efficient.(Mohan, S, 2000) The various options available in the 4WD systems have different placement of the various components which make up the architecture of a 4WD vehicle leading to difference in their traction control system and vehicle dynamics. This paper reflects over the differences and comparisons of the mechanisms of these advanced 4WD options available across multiple range of vehicles and explains the usage of these systems on different terrains.

## Structure

The structures of typical AWD, 4WD transmissions are shown in figure1. The mechanical functioning in the engine is modified by the transmission and is distributed to the wheels of the vehicle by the transfer case through the drive shafts and the axles (Mohan, S, 2000).




1) Internal Combustion engine, 2) Clutch / Torque converter, 3) Gearbox, 4) Rear Differential, 5) Rear Propeller (longitudinal) Shaft, 6) Transfer Case [with central differential and gear reductor (optional)], 7) Front Propeller (longitudinal) shaft, 8) Front Differential, 9) Coupling Device (viscous, electromagnetic)

**Figure 1:** The structures of typical AWD, 4WD transmissions

**Engine**-An engine is the powerhouse of the vehicle. Vehicles usually have engines which are fuel injected(IC-Internal Combustion) and are controlled by an ECU(Electronic Control Unit).(Mohan, S, 2000) The Spark-Ignition unit, which gives fast response times and allows power control in small ranges is responsible for the combustion of the fuel to generate torque.(Mohan, S, 2000) This torque is transferred from engine to the transmission through the crankshaft via the flywheel to the input shaft of the transmission using clutch or hydraulics which is then divided between the wheels.

**Transmission**-The transmission(gearbox) delivers the torque and speed conversions generated by the engine to the wheels using gear ratios according to the variation of speed. The input shaft of the transmission is connected to the crankshaft of the engine of the vehicle and the output shaft(drive shaft) of the transmission is connected the axles, which in turn power the wheels through the differential(s). A transmission consists of some key elements such as gear, gear ratio, clutch, transmission, shift lever and the H pattern. A vehicle can either have an automatic transmission or a manual transmission but other transmission such as CVT(Continuously Variable Transmission) are also gaining popularity.(Staff, 2017) In manual, the driver has the full control. By engaging the clutch which disengages (disconnects the engine from the input shaft of the transmission) the engine from the transmission, the driver can select the required gear in 2WD and also engage the part time modes of 4WD via the levers on the transfer case. In automatic transmission the shifting of gears is handled by the fluid dynamics and the hydraulics. In automatic transmissions, the integration of traction control system to control the torque to the wheels is fairly easy

(Staff, 2017) In a CVT, rather than using the gears, a belt between the two pulleys is used. One of the belt is driven by the shaft of the engine while the other is driven by the differential unit and drive axles. Both of the pulleys are split up so the halves of these pulleys can come closer and farther apart. With the lowering and the high movement of the belt, the gear ratios can be changed between the driving and the driven shaft (Chaikin Don, 2015)

A 'Transaxle' operates in a same manner as that of the transmission. In a typical transmission the transmission is connected via long driveshaft to the rear axle. Whereas, in a transaxle, the output shaft drives a larger gear with is coupled with the differential's ring gear directly. The differential axle which is mounted on the rear axle in a RWD vehicle, is located in the transaxle housing. It is mounted parallel to the transmission. Thereafter, the differential distributes the power to the front two wheels via halfshafts (Chaikin Don, 2015).

For 4WD systems, the transmission system gets a combination of differentials and transfer case depending on the type of 4WD.

The schematic illustration in figure 2 shows the basics of the transmission:

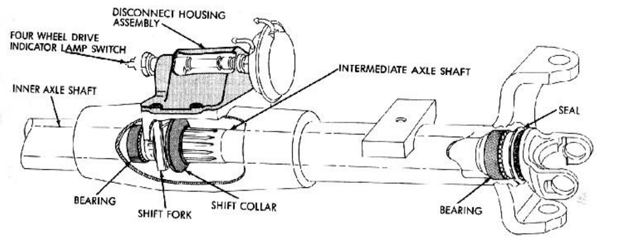



**Figure 2:** The basics of the transmission (http://www.svseeker.com/wp/sv-seeker-2/sailboat/propulsion/engines-and-more)

**Axle**: The axle is a rod which connects to the wheel(s) of an automobile. The axles houses the differentials and drive shafts to each wheel. The output shaft from the transfer case powers the input gears of the axle differential. Typically, the axle is connected to the chassis of the automobiles via the suspension system and bears a significant weight of the automobile on itself. The axles allows the wheel to rotate at different speeds when the vehicle is in turning motion by distributing the torque between the wheels through axle differentials. The axles can typically be classified as of two types: live axles and dead axles. The live axles power the vehicle whereas the dead axle freely rotates. The dead axle can also be engaged and function as a live axle when the vehicle switches to 4WD mode (Mohan, S, 2000).

**Transfer Case**: A transfer case is an additional gear box used for the 4WD architecture. The work of the transfer case is to split the engine torque coming through the transmission and delivers the torque to the output shafts which connect to the driveshafts of both the front and back axles (http://www.fourwheeler.com/how-to/68958-how-transfer-cases-work). The torque ratio of the front axle (%F) to the rear axle(%R) is known as the torque split ratio(F:R) of the transfer case (Mohan, S, 2000). The typical transfer cases can have multiple modes of operation. The switching among different modes can be either electric or manual. The transfer case can also have an additional option of 'low range' which helps to provide greater gear reduction to provide extreme torque support to wheels on challenging terrains. A transfer case can fundamentally be classified in two types for a 4WD vehicle:

**Part Time Mode-**In part time mode, both the front and rear axles are coupled in the transfer case. Since there is no inter-axial differential in this system, any speed differentiation in the axles can cause transmission 'wind-up'. Hence, the vehicle normally operates in 2WD mode and the 4WD should be engaged on loose surfaces where the wind-up in unlikely. In part time, options based on gear ratios such as 4WD High(Four Wheel mode for high speeds and torque) and4WD Low(Four Wheel mode for lower speeds and extreme torque demands) can also be present.(Mohan, S, 2000)

**Full Time Mode-**In full time mode both the axles are powered at all times. The inter-axial differential allows the axles to rotate at different speeds avoiding transmission 'wind-up'. If the inter-axial differential is locked, the vehicle can perform as a part time 4WD. The general torque split between the axles is 50:50 which can be varied with the introduction of different types of differentials. A vehicle that permanently operated in Full Time Mode is often termed as AWD (All Wheel Drive). But, the AWD lacks the ability to lock the inter-axial differential disabling its ability to act as a part time mode limiting their off-road ability on challenging terrains.(Mohan, S, 2000)(http:// www.fourwheeler.com/ how-to/68958-how-transfer-cases-work)

With developments in technology, "One-Demand Mode" has also been introduced into 4WD. In this mode, the vehicle mostly operates in 2WD. The torque to the secondary axle is transferred "on demand" by the vehicle, by the modulation of transfer clutch from 'Open' to a rigidly coupled state and also avoiding the driveline wind-up. The modulation done in the torque can be done by electronic or hydraulic control systems based on wheel slippage.(Mohan, S, 2000) The schematic illustration in figure 3 shows the basics of the transfer case system.

**Differential**: A differential is a mechanical device which balances the torque between the wheels. The inter-axial differential (Center Differential) is positioned in the transfer case or between the two output shafts. The axial differentials are present on the axles of the vehicle, between the axle driveshafts connected to the wheel. The input rotation (transmission output) in the differential gets distributed to the two outputs (axle driveshafts). In 4WD vehicles, the front wheels rotate more swiftly as compared to the rear wheels. Hence, a differential provides the axles to have the ability of turning at different speeds (Mohan, S, 2000).

Depending on the type and modulation based on specific preferences of a 4WD vehicle, the number, type and the placement of differential(s) also varies. A Part Time 4WD has one differential on each axle whereas in Full Time 4WD and AWD there is a center differential along with the axle differentials.= (http://www.4wdonline.com/A/Diff.locks.html)

A standard differential, often termed as an 'Open' differential is suitable when the wheels are on a surface with high traction. If any one of the wheels loses traction, then all the torque of the axle attached to the particular wheel(s) will be directed to the free tire(wheel which has lost the traction) due to the phenomena of "Path of least resistance". Hence, to avoid the direction of the power to the free wheel and rather direct it to the wheel with traction, 'differential locks' are introduced. These differential locks play a vital role in 4WD vehicles. There are various types of differential locks present in the market such as: Limited slip differentials, Torsen Differentials, Detroit Differentials, Selectable Lockers, Spools (http://www.crawlpedia.com/locker_comparison.htm)

## Basic vehicle dynamics and traction

According to inertia, a body in rest or motion, will always try to maintain the status it is in. In order to bring change to the status, external forces have to applied to the body. There are various forces which act on the body regardless of its state of motion such as gravitational force. According to figure, in a vehicle, apart from the gravitation force acting on it due to its weight, there are various different types of forces which act on it. These forces can be distributed along the longitudinal axis (Example: rolling friction) or laterally (Example: steering force) as illustrated in figure 4 (Reif, 2014).

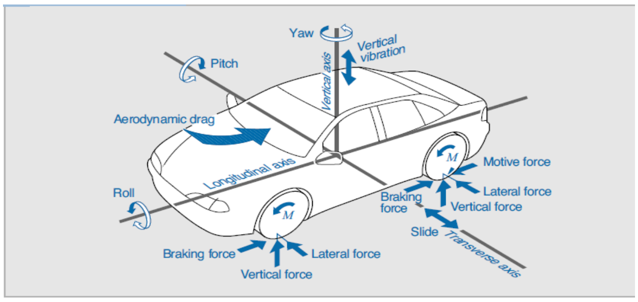



**Figure 4:** Distribution of forces on a vehicle (Reif, 2014)

In order for the vehicle to move, the engine torque must overcome all the forces which resist the motion such as the friction between the tires and the road. The forces which act on the tires make the vehicle change its direction or move in a specific way. The forces can be the circumferential force, vertical force (normal force) or the lateral force. The circumferential force is produced by the transmission(torque) or the brakes(frictional force) which make the vehicle increase or decrease their speed. The vertical forces are the forces between the tires and the road which acts at all the times irrespective of the state(motion or rest) of the vehicle. The part of the tire in contact with the road gets deformed due to the vertical force. As the tire turns, this vertical force does not stay balanced so the deformability also changes and a trapezoidal pressure-distribution pattern is produced. The lateral force acts upon the wheels when the vehicle is getting steered or there is a crosswind affecting the aerodynamics of the vehicle (Reif, 2014).

The coefficient of friction (μ) and the contact load (between surface and object) of the tires limit the maximum friction force that can be exerted at the tire patch. Apart from the longitudinal and lateral components of force, wheel slippage is also a factor upon which the traction and steering forces depend. The torque applied to the wheel is directly proportional to the wheel slippage. If the torque is increased, the wheel slippage will also increase to generate traction. Once the applied torque will exceed the maximum traction available at the tire patch, the wheel will obtain a quick-escape slip condition (Mohan, S, 2000)

In the conditions where the surfaces have low coefficient of friction, wheel slippage should be avoided. On surfaces covered with snow, the wheel tries to push the upper layer of the snow which makes the bottom layers to be more compact making the surface with even less μ which further reduces the traction. On surfaces like that of sand and mud, the wheel buries itself into the surface due to the wheel spinning action which then requires more effort by the vehicle to get out (Mohan, S, 2000).

Yaw movements (causing the rear end to swing around) occur on the launch of the vehicle whether the wheels are in straightened or angular direction. During the cornering/turning of the vehicle, the yaw movement is very dependent upon the steering geometry (figure 5) and the speed of the vehicle. During slow turning, the steering angles are significantly high and there is less slide-slip of the tires. If there is improper alignment between the steering geometry and the driveline of the vehicle, it can make the tires follow a path different than that of the vehicle. This can subsequently lead to the driveline and suspension wind up and the release of the formed energy through tire slippage in the surface can lead to the uneven linear and yaw motion. This can also be experienced by the driver through the steering feedback as the steering may stiffen up (Mohan, S, 2000).

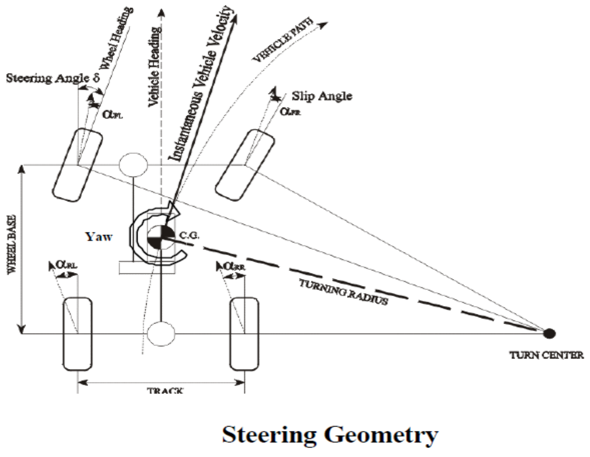



**Figure 5**: (Mohan, S, 2000)

Lateral forces experienced on the tires become significant at higher cornering speeds. To counter these forces, the wheels need to push the vehicle into the desired path which is done with the help of steering forces. The load and the coefficient of the friction are the limiting factors for the total force of friction at the tire. Acceleration and braking can reduce the lateral steering forces at the tires. Having an unbalanced steering force and lateral forces can cause the vehicle to under steer or over steer.(Mohan, S, 2000) A vehicle under steers when the lateral acceleration increases, due to which the front axle lateral slip angle increases more than that of the rear axle lateral slip angle. When the rear axle lateral slip angle is more than that of the front axle lateral slip angle, the vehicle over steers. When the centrifugal force acting on the vehicle becomes more than the lateral forces acting on the wheel, the vehicle shifts from the desired course. The vehicle will under steer if it slips at the front wheel and over steer if it slips at the wheel axles (Reif, 2014).

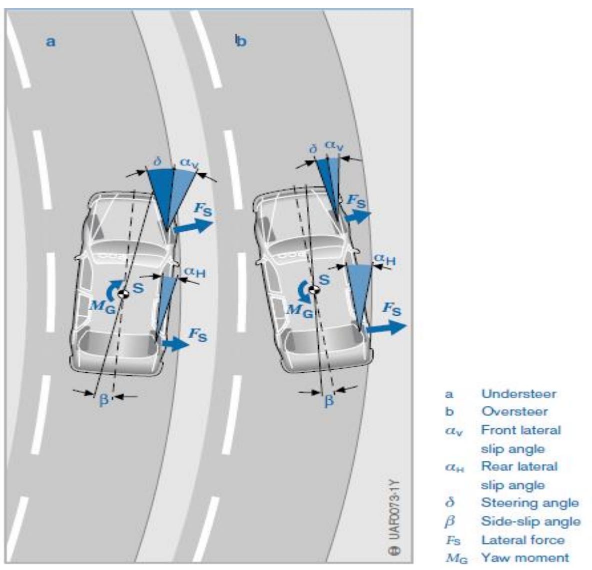



**Figure 6:** (Reif, 2014)

The directional stability of the vehicle is important to move the vehicle in intended direction. Traction Control System (TCS) is a sort of dynamic security control framework, which may enhance a driver's capacity to control a vehicle under unfavourable conditions. For instance, a wet or frozen street and control the slip proportions of driving wheels work in the ideal traction execution conditions in the order to augment the traction power between the vehicle's tires and the street. At exhibit, rationale edge technique in view of tests is broadly utilized as a part of TCS (Liu Z, 2011).

Traction control system is not the newly developed technology and also there has been always the need of such system in hilly areas. The root of the system lies in 1950's where the system was originally developed for airplanes but further have been optimized by the automotive engineers to be used in cars to enhance the safety on roads. The system was first introduced by Mercedes Benz in 1987, further BMW came into the privileged once and later it was implemented in Supra (Liu Z, 2011).

The system is completely based on the spinning of the wheels. Once it senses the significant fasting of one wheel over the other it invokes ABS(Anti-Braking System consisting of ECU-Electronic Control Unit) and hence brakes create friction to the wheel spinning with lessened traction, as a outcome of this mechanism the power is transmitted to differential. Hence to be equipped with this technology, each wheel should be equipped with speed sensors and the ECU should be designed accordingly (Liu Z, 2011).

## Conclusion

The infusion of technology into the fundamental architecture of 4x4 Transmissions has helped to make the vehicles more secured, automated and more power efficient. While there will always be a segment in the market which would prefer the simple transfer case and Part Time 4x4 mode which are less electronically complex, the future will bring the advancements which will be more technologically dependent benefitting the more tech savvy segment. Introduction of the traction control systems have made the vehicles more capable in their performance on both off-road and on-road surfaces by keeping the driver's safety as a priority. As it is still a newly developed technology having a complex functionality, the technology incorporated into the advanced 4x4 transmissions such as AWD and Full Time 4WD still has a long way to go. These lesser technologically complex system such as the Part Time 4WD still overshadow the present advance systems in performance in many harsh environmental conditions. As these advanced systems are more electronically dependent today, failure of a single component such as speed sensors can lead to multiple failures in the system whereas the fundamental mechanical devices are more rugged and durable. These electronic components in an advanced technological system can be adversely affected by the harsh environmental conditions. Future promises the advanced systems to be more secure and efficient, making the technology incorporated in these systems to be more lighter, transparent, efficient and safe. Therefore, the fundamental mechanical devices should be considered as a more promising option in the present time.

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