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All-Wheel Drive / Four-Wheel Drive Systems and Strategies

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Modern Four-Wheel Drive (4WD) systems have become very sophisticated and infused with electronic control technology. These 4WD vehicles offer the appeal of an active lifestyle made possible by the assurance of a safe and secure vehicle, on- and off-road, along with the improved hauling and towing capabilities for people and equipment. The emphasis has been shifting from mere traction enhancement to on-road safety and handling improvement. There has also been a successful move to incorporate the above benefits in smaller, more fuel-efficient Front-Wheel-Drive (FWD) based vehicles generally called All-Wheel Drive (AWD) systems. This paper attempts to explain the control tactics, strategies and the philosophies behind various traction control systems.

Keywords: Four-Wheel-Drive, All-Wheel-Drive, Traction control

INTRODUCTION

Four-Wheel Drive (4WD) systems have come a long way since the 1940s. From simple mechanical devices applied in military utility vehicles, they have evolved into the sophisticated systems infused with control technology that are available in modern, high speed, on-road vehicles. The improved mobility attained in difficult terrain by providing traction on all four tire patches was the major incentive to incorporate 4WD systems in drive trains. The early systems were cumbersome to engage into 4WD and required driving skills beyond the capability of the average driver. The popularity of 4WD vehicles has soared because of the appeal of an active life style made possible by the assurance of a safe and secure vehicle, on- and off-road, along with the improved hauling and towing capabilities for people and equipment. Only lately have the 4WD systems themselves become more user friendly. Since most people use the 4WD vehicles as on-road transportation, the emphasis has been shifting from mere traction enhancement to on-road safety and handling improvement. At the same time, there has been a successful move to incorporate the above benefits in smaller, more fuel efficient front-wheel-drive (FWD) based vehicles. These drive line architectures are generally called All-Wheel Drive (AWD) systems. This paper attempts to explain the control tactics and strategies and the philosophies behind various traction control systems. Towards this end, the paper also recounts for ready reference, the basic vehicle dynamics principles involved in the description of a vehicle's performance.

BASIC DEFINITIONS

4WD/AWD systems were developed in many different geographic markets and across different vehicle platforms, and so there is no universally accepted set of terminology to describe the various functions and architectures. In this and the following sections we will describe the generally accepted nomenclature along with some of the regional variations.

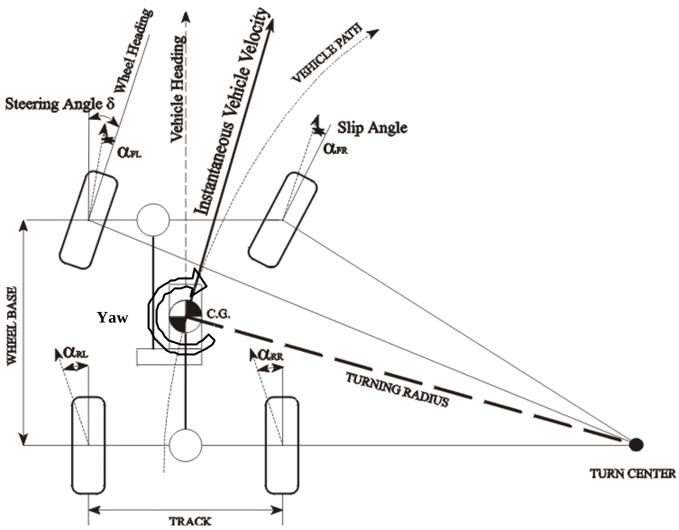

Figure 1 Steering Geometry

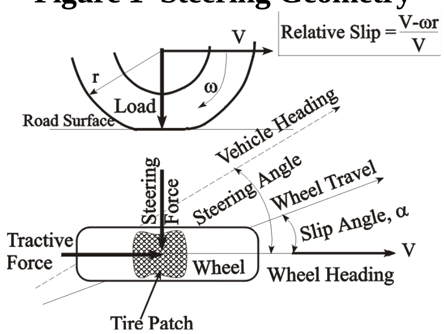

Figure 2 Tire Patch

The Ackerman steering geometry of a typical front wheel steered vehicle is shown in the Figure 1. As seen from the drawing, during a turn, the outer wheels must travel a longer path and so must rotate faster than the inner wheels. Similarly, the front axle must turn faster than the rear axle. If the driveline does not permit these differences in speeds, there could be undesirable driveline wind-up, especially on dry pavements where the relatively high surface friction prevents the tires from slipping easily. This could lead to poor fuel economy, undesirable tire scrubbing ('crow-hop') and damage to the driveline even during moderate maneuvers.

DRIVELINE ARCHITECTURES

Typical 4WD/AWD drivelines are shown in Figures 3 and 4. The engine rotation is modified by the transmission and distributed to the wheels by the transfer case through the propeller or drive shafts and the axles. The key characteristics of the various elements relevant to traction control will be summarized here.

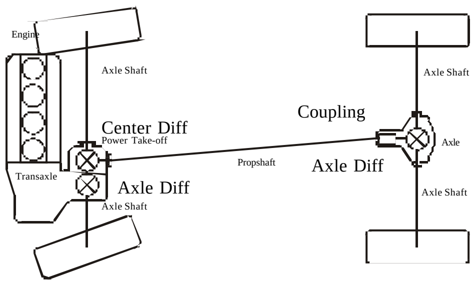

Figure 3 AWD Vehicle

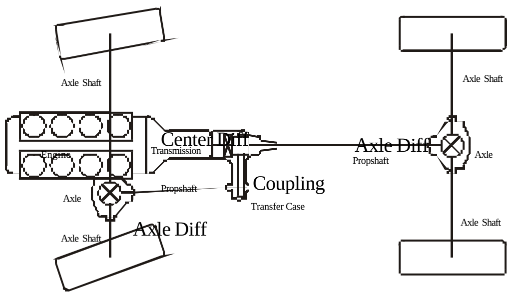

Figure 4 4WD Vehicle

THE ENGINE - Modern vehicles have engines that are typically fuel injected and controlled by an electronic control unit. Ignition spark control allows the engine power to be controlled in small ranges, but with quicker response times. Direct fuel control affords a wider range of power regulation but with a somewhat slower response time.

THE TRANSMISSION - In manual transmissions, as the name implies, the control is left up to the driver. Automatic transmissions, especially the electronically controlled ones can be easily integrated into traction control systems to control the torque to the wheels.

THE TRANSFER CASE – This may also be called Transfer Gearbox, Power Take-off Unit, PTU or PTO. This is an additional gearbox used to get the 4WD architecture. In Rear Wheel Drive (RWD) based vehicles, the Transfer Case distributes the torque to the two axles via the propeller shafts. In Front Wheel Drive (FWD) based vehicles, the Power Take Off Unit allows the drive shaft to the rear axle to be connected to the transmission. The ratio of the front axle torque (F%) to the rear axle torque (R%) is called the torque split ratio (F:R) of the transfer case. Some transfer cases have an added 'low range' to provide extra gear reduction for extreme torque demands at lower speeds. Typical transfer cases are designed to have multiple modes of operation. Depending on the implementation, the selection of the operating mode could be manual or electric and the switching times and the preconditions for switching might vary. The primary modes are described below.

Two Wheel Drive (2WD) Mode - In this mode only one axle (typically the rear axle) is driven. The drive to the other axle is disconnected. The operating torque split ratio is 0:100.

Four Wheel Drive (4WD) Mode - Here, depending on the nature of torque transfer to the axles, we can define three sub-modes.

Part-time Mode - The front and rear axle drives are rigidly coupled in the transfer case. Since the driveline does not permit any speed differentiation between the axles and would cause driveline wind-up, this mode is recommended only for 'part-time' use in off-road or loose surface conditions where driveline wind-up is unlikely. Depending on the road condition and the weight over the axles, up to full torque could go to either axle.

Full-time Mode - Both axles are driven at all times, but an inter-axle differential permits the axles to turn at different speeds as needed. This allows the vehicle to be driven 'full-time' in this mode, irrespective of the nature of the road surface, without fear of driveline wind-up. With standard bevel gear differentials the torque split is 50:50. Planetary differentials can provide asymmetric torque splits as needed. A system that operates permanently in the full-time mode is sometimes called the 'All-the-Time 4WD', 'All-Wheel-Drive' or 'AWD'. If the inter-axle differential is locked out, then the mode reverts to a 'part-time mode'.

On-Demand Mode - In this mode, the transfer case operates primarily in the 2WD mode. Torque is transferred to the secondary axle 'on-demand' or as needed, by modulating the transfer clutch from 'open' to a rigidly coupled state, while avoiding any driveline wind-up. The torque modulation may be achieved by active electronic/hydraulic control systems, or by passive devices, based on wheel slip or wheel torque, as described in the section on traction control systems.

In addition to these basic modes, there could be implementations that combine these modes. For example, the system could have a clutch across the center differential, capable of modulating the front axle torque from a Full-time mode with the 30:70 torque split of the center differential rather than from the 0:100 torque split of the 2WD mode.

AXLE – The axle consists of the structural housing, differential and the drive shafts to each wheel. A propeller shaft from the Transfer Case drives the input gear of the axle differential. The axles allow the wheels to rotate at different speeds during turns by distributing the torque through the axle differential. The rigid axle unit, which integrates all above elements, is typically connected to the chassis via the suspension elements. The independent axle unit, housing just the differential is rigidly attached to the chassis and half shafts and Constant Velocity (CV) joints connect the outputs from the differential to the wheels that are connected to the chassis via the suspension elements. The axle drive shafts could be permanently connected to the wheels (live axles) or could permit disconnecting the wheel(s) (disconnect axles) to prevent drag losses when the axle is not being driven. The disconnect device could be a manual or a power-actuated mechanism.

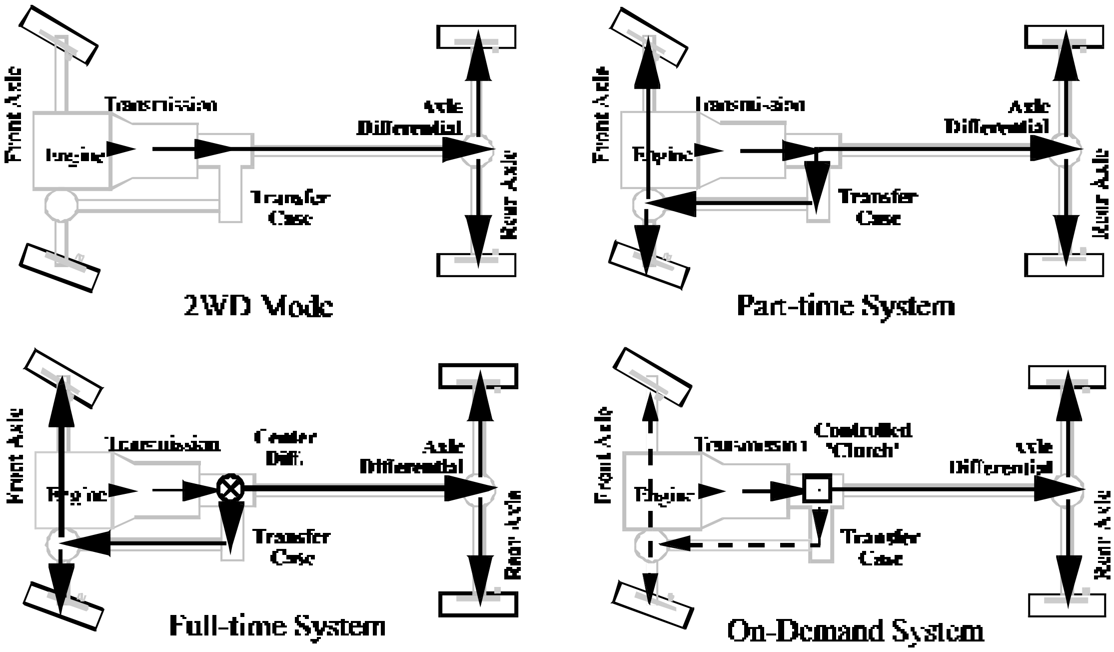

Figure 5 4WD Modes

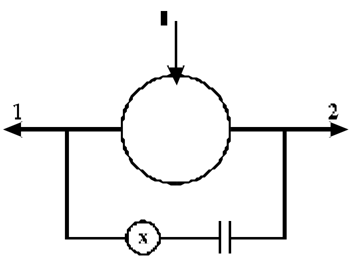

Figure 6

DIFFERENTIAL - The center differential is located in the transfer case or the PTU, between the two outputs. The axle differential is in the axle, between the two axle drive shafts.

The differential distributes the input rotation to the two outputs that are allowed to turn at different speeds, and can be thought of as a torque balancing device between the two driven elements. A schematic drawing of a generic (bevel gear or planetary) differential is shown in Figure 5. The 'open' differential does not have the optional torque bias device ‘x’ shown. In ‘true’ differentials, if one of the outputs slows down, there is a corresponding speed up of the other output. In other words, the input speed always remains the average of the two output speeds. This kinematic relationship also constrains the input torque in such differentials to be limited by the smaller of the two output torques. The biasing device ‘x’ across the differential partially removes this limitation and allows the differential to transmit more torque to the outputs than an open differential. This biasing may be dependent on the speed difference between the two outputs (speed sensitive limited slip), the torque at the outputs (torque sensitive limited slip) or some external criterion as determined by a control logic (active, intelligent limited slip). In some quasi-differential devices, the differential action is achieved simply by permitting one output to overrun the other.

BASIC VEHICLE DYNAMICS

The primary motive forces on the vehicle are applied at the tire patches in contact with the road surface. The total maximum friction force at the tire patch is limited by the contact load and the coefficient of friction (μ) with the road. The longitudinal component of this force is the maximum available tractive/braking force and the transverse or lateral component is the maximum available steering force. The actual traction and steering forces will also depend on the wheel relative slip, the wheel slip angle and the road condition as shown in Figures 7 and 8. It must be noted that ‘on-road’ surfaces generate peak traction at relatively low slip where as ‘off-road’ surfaces like gravel generate maximum traction at much higher slip.

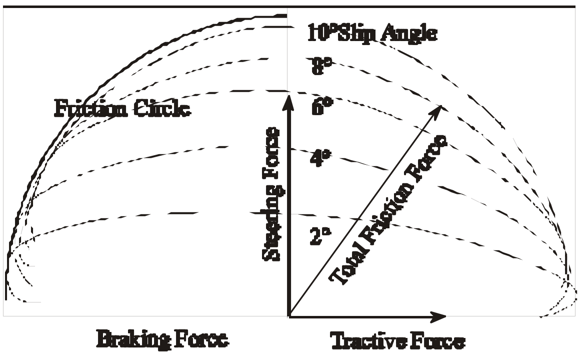

Figure 7 Friction Circle

Referring to Figure 8, if the applied wheel drive torque is increased, the wheel slip at the tire patch increases to generate the traction. The initial slip mechanism is due to elastic deformation of the tire walls. The slip gradually increases as the treads start sliding on the road. Once the applied torque exceeds the maximum traction available at the tire patch, the wheel will get into a run-away slip condition as may be seen in Figure 8. Even if only one of the wheels slips, the traction at an axle is reduced due to its influence on the other wheel through the open differential. In addition to the loss of traction, the available steering force also reduces at the slipping wheel and this affects directional stability of the vehicle. As discussed earlier, drivetrains, especially with open differentials will lose overall traction at an axle if either or both of the two wheels lose traction. This would happen if the road surface provides a low coefficient of friction (μ) with the tire. It could also happen if the load at the tire patch is reduced due to dynamic load transfer or due to suspension effects.

During vehicle launch from low μ surfaces, tire spin up should be avoided to reduce the chances of getting stuck. On snow covered surfaces the problem occurs because the spinning tire tends to push away the top layer, compact the inner layer and polish it into an extremely low μ surface further reducing available traction. On sand or mud, the spinning action buries the wheel and increases the effort needed to get out.

Tire spin up during launch, even with straightened wheels, would cause the vehicle to be susceptible to yaw disturbances and cause the rear end to swing around or ‘fishtail’. With steering input, as during cornering, the vehicle behavior is very dependent on the speed. In low speed turning maneuvers, the steering angles are typically high and tires roll without much side-slip. But due to imperfections in the steering geometry and driveline couplings there could be some tire scuffing. This effect would become pronounced if the drivetrain does not permit speed differentiation either within or between the axles. The driveline and suspension wind-up and subsequent release of this energy, through tire slippage on the road surface, results in an uneven combination of linear and yaw motion. This movement known as 'crow-hop' could be annoying in the least or cause driveline failure at the worst. The effect also feeds back to the driver as a stiffening of the steering effort.

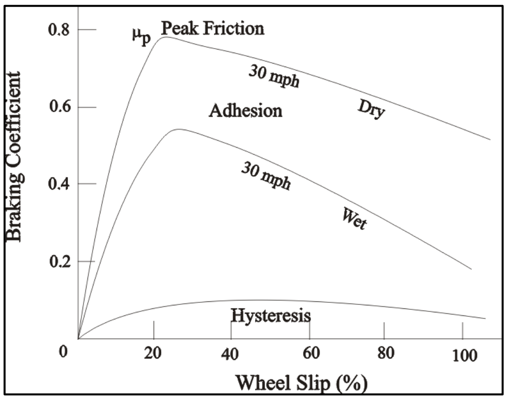

Figure 8 Traction vs Slip

At higher cornering speeds, the lateral accelerations experienced by the vehicle become significant. Lateral steering forces are required at the wheels to push the vehicle into the desired path. This requires all the wheels to operate under some side slip condition. As described in the sections on tire patch mechanics and vehicle dynamics, the load and the coefficient of friction limit the total friction force at the tire. So acceleration or braking during cornering could reduce the available lateral steering forces at the tires. If this happens at the front wheels, the vehicle would want to go straight, turn less than intended and understeer. If the rear wheels have insufficient steering force, they slide outward and the vehicle would turn into the corner and oversteer. Any other phenomenon like dynamic load transfer or camber change due to the suspension will change the magnitude and or direction of the steering forces at the tires and will influence the cornering ability.

Braking also could affect the vehicle’s handling ability. Premature lock up of the front wheel during braking will cause loss of steering ability. If lock up occurs at the rear wheels, the stability of the vehicle itself is compromised and the vehicle might end up spinning about its vertical axis due to amplification of any yaw disturbance.

NEED FOR TRACTION CONTROL

The ideal drivetrain allows the driver to propel the vehicle in the intended direction and speed in a manner that promotes the ease and ability to maintain control. This requires not only a capacity to respond to the driver's inputs in a predictable manner but also the ability to feed back useful information to the driver. In the final analysis, it is the performance of the driver/vehicle system (loosely called the 'handling') that is important in assessing the success or limitation of a particular traction control implementation. Although the primary contributor is the drivetrain, the steering, suspension and braking systems also influence the vehicle's handling performance. Ultimately, the laws of physics dictate the static and dynamic limits of performance of the vehicle under all road, load and speed conditions.

The typical driver uses the vehicle, most of the time, well below its dynamic limit. It is desirable to enhance the tractive/braking ability and the directional stability of the vehicle, thus allowing the driver to expand the envelope of performance without reducing safety and the sense of control. This in essence is the purpose of the traction control system. To restate this in simpler terms, the traction control system should improve the mobility at low speeds and in difficult terrain by improving the tractive performance, and improve the safety and handling at higher speeds by improving the directional stability. To the average driver, this would translate to better performance and safer handling even under adverse driving conditions. The ways in which traction and directional stability might be compromised was described in the previous section on vehicle dynamics.

TACTICS FOR TRACTION CONTROL

Before we discuss the strategies of control, let us look at the tactics available for control. Since the only active external forces on the vehicle comes from the tire patches, our sole option is to control or influence the tire patch dynamics. As seen earlier, the effective maximum friction force obtainable at each tire patch is governed by the normal force and the available coefficient of friction, both of which are difficult to influence. Many independent suspension systems maintain tire/ground contact by allowing a larger jounce range for the wheels. Some advanced active suspension control systems do adjust the effective dynamic load at the tire patch. But mostly we have control over only two of the key elements. First, the apportioning of the tire force between the tractive and steering forces may be controlled by manipulating the tire slip angle via the steering (Figures 2 and 7). Second, the maximum available tire force may be controlled by adjusting the tire slip at the tire patch (Figures 2 and 8). Most control systems leave the steering to the driver and attempt to control the tire slip to achieve both traction and stability improvement. Taking a closer look at Figure 8, we realize that the operating point along the slip curve is determined by the matching of the maximum available resisting force at the tire patch and the applied torque at the wheel. Under quasi steady-state operation, within the peak limit, if the applied torque is altered, the tire slip changes till a matching tire force can be generated. Beyond the peak limit, of course, there is runaway slip of the tire. This opens up three avenues for control.

1. Reapportion the applied torque among the wheels. This is the approach taken by all limited slip differentials and on-demand torque transfer clutches.
2. Control the amount of applied torque in the drive train. This is the approach taken by engine and transmission control integration with traction control (power management).
3. Absorb the excess torque at the tire patch. This is the approach taken by the brake based traction and stability control systems (eg. ESP- Electronic Stability Program).

	Tire Patch Torque Control			
	Reapportion Torque	Control amount of Torque		
		Reduce Torque		Increase Torque
		Reduce applied Torque	Absorb excess Torque	
Control Devices	Limited Slip Clutches	Power Management	Selective Brake Application	Active Torque Control

Figure 9: Tire Patch Torque Control

Limited Slip Differentials And On-Demand Torque Transfer Clutches. These devices may be passive devices with operating characteristics dependent on some intrinsic physical phenomenon inherent to the device or active devices that use an external logic to control their characteristic. Passive units widely used are the slip sensitive mechanisms like the viscous or Gerodisc couplings as well as the torque sensitive devices like the Torsen or the Suretrac differentials. All active clutches use a control system that utilizes other vehicle operating parameters to decide when, how long and how strongly to activate the clutch. The extent of these control systems is defined by technical considerations like the level of complexity and adaptations required as well as by cost considerations. Obviously, the active clutches lend themselves to integration with other vehicle subsystems for a more effective overall traction and stability control system.

Power Management. As mentioned earlier, most modern engines and automatic transmissions are electronically controlled and may easily be adapted and integrated into the traction and stability control system.

Brake Based Traction And Stability Control Systems. Lately a number of systems have been introduced in the market based on the principle of selectively applying the individual wheel brakes to achieve slip reduction, descent control or yaw control.

Yaw Control. Yaw motion is the rotation of the vehicle about the vertical axis through its center of mass and the 'yaw-rate' is the speed of that rotation. The effect of the external applied forces about the axis through the center of mass is the ‘yaw-moment’. Vehicle motion along the road surface may be thought of as a combination of linear and

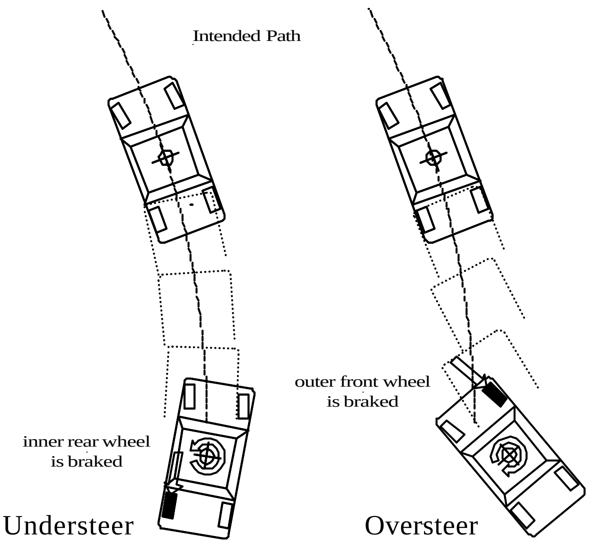

Figure 10 Yaw Control

yaw motion. Ideally, during straight line launch, there is no yaw motion. Any yaw indicates an imbalance or left to right assymetry in the tractive forces at the wheels. During cornering, the vehicle yaws at a rate proportional to the linear speed (V) and inversely proportional to the turning radius (r). Under rolling or no-slip conditions, the steering angle, wheelbase and the track of the vehicle determine its turning radius. The vehicle also experiences a lateral acceleration corresponding to (V^2/r). By measuring the individual wheel speeds, steering angle, throttle position, brake pressure and lateral acceleration, the control system can determine the driver’s intent and the desired yaw-rate. To judge the vehicle’s response to the driver input requires the additional measurement of the actual yaw-rate using a yaw-rate sensor. Comparing the desired to the actual yaw-rate allows the controller to apply corrective yaw-moment.

The brake based yaw-rate control is an extension of the Antilock Brake System (ABS) and shares many of its components. The control program selectively applies the brakes of the four wheels to create a correcting moment to offset the yaw-rate. Typically, as illustrated in Figure 10, oversteer may be countered by the application of the outer, front wheel brake and understeer may be countered by application of the inner, rear wheel brake. Although quick acting, effective and acceptable, this method is essentially a braking maneuver and so reduces the speed performance slightly.

Recently some carmakers have introduced yaw control based on intentionally varying the torque split between the wheels to generate the desired yaw-moment. The additive tractive effort might give them some advantage over the subtractive nature of the brake-based systems. It is too early to say whether these systems offer significant performance improvements consistent with the added mechanical complexity, weight and cost.

CONTROL SYSTEMS STRATEGIES

There is no universal strategy that will satisfy all types of drivers under all kinds of driving conditions. The particular strategy employed depends on the limitations of the vehicle, the philosophy behind the calibration and of course cost. Advances in electronics and miniaturization and micromachined sensors have allowed the development of sophisticated systems that are fast enough to do the real time computations necessary and yet are small enough to be packaged and affordable. As the cost of providing advanced technology comes down, it becomes feasible to apply it more universally. It also becomes increasingly desirable to coordinate and integrate the control of the various vehicle subsystems like engine, transmission, steering, brakes and suspension and benefit from their interactions rather than allow them to operate independently.

The philosophy that defines the calibration or tuning of the control system is dependent on the relative emphasis placed on making the vehicle safer for even the unskilled driver and the desire to enlarge the operating envelope of the vehicle under adverse driving conditions. The control system should minimize abrupt changes in the behavior of the vehicle within its extended operating envelope. It should also be predictable and provide sufficient feedback and warning to the driver when approaching the vehicle’s critical dynamic limits.

Some carmakers, with safety in mind, have chosen to intervene aggressively and early on to prevent the driver from pushing the vehicle beyond ‘safe’ limits. This approach necessarily involves power management and takes away absolute throttle control from the driver close to these limits. Other manufacturers, with an eye on performance, have allowed the driver some leeway in applying minor corrections using steering, throttle and brake and enforce throttle and brake control only to prevent the vehicle from losing total control and becoming unsafe.

Many of the current systems allow the driver to switch off the traction control setting. It is quite possible that in the future, manufacturers can allow the driver the option of a graduated calibration setting somewhat similar to the 'soft' and 'sporty' setting seen in some electronically controlled automatic transmissions.

SUMMARY

Even though there will always be a market segment that utilizes the simple, stand-alone transfer cases and PTUs, the advanced traction control systems of the future will benefit from integration with the other subsystems like engine, transmission, brakes and suspension. The thrust will be to enhance the traction, stability and safety of the vehicles under adverse, off-road as well as high speed on-road driving conditions. The specific control strategy employed should take into consideration the nature of the vehicle, the anticipated driving pattern, the expectations of the driver in that market segment and the relative emphasis placed on safety and performance. Technological advancements will ensure that future traction control systems will be more transparent, safer, lighter, more efficient and more complex in a 'systems' sense.

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