

The Influence of Direct Yaw Control AWD Systems on Vehicle Stability and Response in All Driving Conditions

Bill Post, Xiaodi Kang and Theodore Klaus

Honda R&D Americas, Inc.

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ABSTRACT

Driveline torque distribution has long been a research topic, and in the last several decades research has been directed towards enhancing on-road vehicle stability and agility through application of controllable driveline systems. This paper discusses the impact of Direct Yaw Control AWD systems (DYC AWD Systems) on the combined acceleration and turning performance as it pertains to maneuverability and stability on all road surfaces. To achieve higher levels of both safety and performance, the application of a controllable DYC AWD system capable of applying direct yaw moment to the vehicle chassis serves as a key goal to achieve the optimal result. A classification of existing driveline systems is discussed and compared to these optimal requirements. Representative on-vehicle scenarios are discussed to illustrate the impact of AWD control on the vehicle stability and maneuverability and to highlight the effects to the vehicle operator. Finally, the integration of the AWD feed-forward control with feedback control demands from a yaw stability control algorithm are discussed.

INTRODUCTION

Driveline system design is affected by a variety of factors such as cost, weight, packaging, etc. Of the various designs and constructions, each has its own fundamental character and function. Some designs are oriented towards off-road traction, others towards part-time function, and some towards on-road performance (1,2). Invariably, the design constraints and vehicle level targets often lead to specific choices that determine the final tradeoff between various performance traits.

Some customers use their vehicles in severe off-road conditions such as steep slopes and in deep mud; and, hence some driveline systems are specifically oriented towards this area. However, generally, customers use their vehicles for on-road driving on a regular basis. Because of this, a vehicle's on-road performance is an important aspect to the overall safety and performance of the vehicle. On-road conditions vary from day to day

according to weather; and, various geographic regions have their own characteristics. Accordingly, an AWD system's operation should provide similar characteristics in order to provide driving confidence and security to the driver. One such characteristic that is important for driving confidence and hence dynamic safety is the ability of the AWD system to produce accelerating and turning results that are reasonably consistent across a wide range of driving conditions.

LINE TRACE DYNAMICS DURING COMBINED ACCELERATION AND TURNING

AWD systems have the inherent capability to distribute torque to the various wheels of the vehicle under driving (and sometimes engine coasting) situations. The overall effect of the distributed driveline torque generally contributes to understeer or oversteer depending on the surface condition of the road, the vehicle speed and the lateral acceleration level. As pointed out by Williams (1,2), many of the modern AWD systems are constructed from either a FWD or RWD basis and may be part time, full time, on-demand, etc.. The basis from which the AWD system is constructed has an impact on the fundamental behavior of the line trace dynamics. Hence the fundamentals of the line trace dynamics can be discussed at a basic level in the comparison between the behaviors of a FWD vehicle versus a RWD vehicle.

LINE TRACE DYNAMICS OF FWD VEHICLES

In the case of a FWD vehicle, addition of driveline torque to the front axle under turning conditions generally contributes to increased understeer. Since the front wheels are responsible for both cornering and driving force loads, increase of the driving torque requirement reduces the ability to achieve the same cornering result compared to when there is no driving load. As a standard metric to quantify the accelerating and turning line trace dynamics, a simple test can be prescribed termed the R/R_0 test.

In the R/R_0 test, the vehicle is accelerated from an initial radius (R_0) under varying levels of longitudinal

acceleration. At the start of the test, the vehicle is steered around a constant radius (15m e.g.) and the steering wheel is fixed. Then the driver applies throttle to achieve a target longitudinal G (rate of change of speed). To compare the range of possible line trace characteristic, the two limiting cases are 1) just enough throttle to gradually increase the vehicle speed such as in a steady state understeer test, and 2) wide open throttle (WOT) in a specified gear position.

As the vehicle accelerates (either in a quasi-static manner with minimal throttle or in a dynamic manner with large throttle) the instantaneous turning radius (R) can be measured and normalized by the starting radius (R_0). As a comparison tool, the normalized radius (R/R_0) can be plotted against the lateral acceleration to understand the differences between a quasi-static behavior and a limit acceleration behavior.

Figure 1 illustrates the behavior of a typical FWD vehicle for the R/R_0 test. The Steady State ($A_x \approx 0$) line represents the basic understeer behavior of the vehicle; as the vehicle speed increases (and hence the lateral acceleration grows) the R/R_0 deviation from the initial radius is positive ($R/R_0 > 1.0$). This indicates a larger turning radius and hence an understeering tendency. Next, as a measure of the driveline influence, the accelerating and turning ($A_x = 3.0 \text{ m/s}^2$) line shows how much more understeer is generated by sharing the cornering load with the traction load. There is a difference over the entire lateral acceleration range (accelerating line having more R/R_0 deviation than steady state line at a given lateral acceleration) indicating an increase in understeer while accelerating.

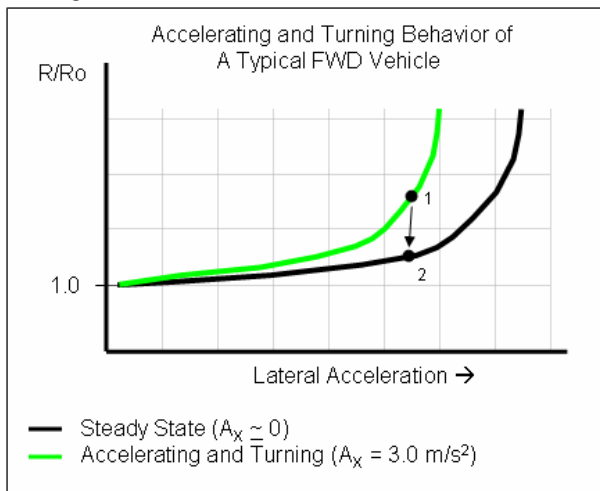


Figure 1: Typical R/R_0 Characteristic of a FWD Vehicle

There may also be a considerable reduction in the maximum obtainable lateral acceleration (the accelerating and turning line reaches an asymptotic behavior at a much lower lateral acceleration than does the steady state line. Simply put, a FWD vehicle creates more understeer under throttle than off-throttle.

A relevant side-effect of this behavior is the line trace characteristic which would occur if the driver were to lift

throttle during a combined accelerating and turning maneuver, commonly called "lift-in-turn" (LIT). While accelerating and turning, the vehicle follows the accelerating and turning line, to point "1" in the figure. If the driver were to lift throttle at this point, the additional understeer created by the driveline forces (and impact to the reduced lateral force capability) would suddenly be removed. The vehicle would then behave according to the steady state line and there would be a sudden transition from point "1" to point "2" in the figure. This typically results in a yaw rate increase or spin in the direction of the turning center of the radius. This behavior is relatively consistent in nature over a range of road surfaces and lateral accelerations for the FWD vehicle case.

LINE TRACE DYNAMICS OF RWD VEHICLES

A RWD vehicle has a typical but different tendency for the R/R_0 behavior. In theory, the steady state line of the RWD vehicle would be the same as if it were FWD (assuming the basic vehicle weight distribution, etc was not driveline dependent). However, for the accelerating case (especially as large drive torque is applied at the rear axle) the vehicle's understeer behavior changes throughout the range of increasing lateral acceleration.

Figure 2 below shows a typical behavior for a RWD vehicle. Initially, at lower lateral acceleration, the drive torque creates an increase in understeer (similar to a FWD vehicle).

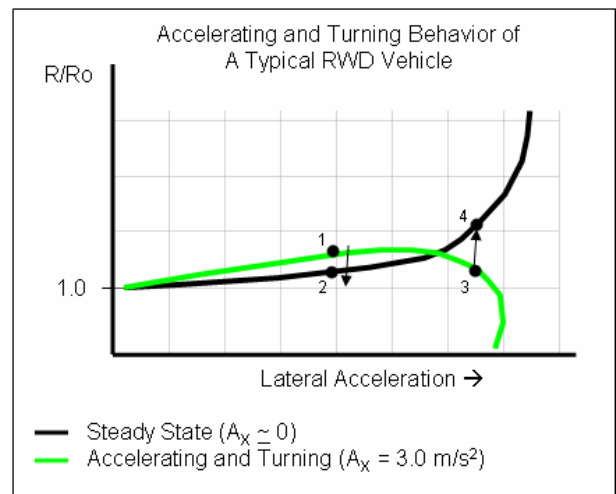


Figure 2: Typical R/R_0 Characteristic of a RWD Vehicle

Then at a medium lateral acceleration the understeer begins to diminish (slope flattens out and becomes negative) as the rear wheels are sharing more lateral load with the tractive load. In many cases, continued acceleration results in a limit oversteer situation where the rear axle loses lateral grip at a faster rate than the front axle ($R/R_0 < 0$). This transition is indicated by the downward trend of the accelerating and turning line in the figure at higher lateral accelerations.

Side effects of this behavior are two-fold depending on the prevailing surface condition of the road, vehicle speed and lateral acceleration. In the low lateral acceleration region, a lift-in-turn (LIT) would produce a mild increase in the yaw rate as illustrated by the transition between points "1" and "2" in the figure (similar discussion as the FWD case but the differences in the two lines at "1" and "2" are smaller for the illustrated RWD case). However, a lift-in-turn at higher lateral acceleration would produce more understeer (transition from point "3" to point "4" in the figure). Because of this apparent reversal of the basic LIT behavior, unskilled drivers may have difficulty to make corrections in the steering to appropriately compensate the changes in yaw behavior associated with the driveline affect. Furthermore, this behavior can become more variable when the road surface coefficient is low.

LINE TRACE DYNAMICS OF AWD VEHICLES

The benefit that an AWD vehicle has over either a FWD or RWD vehicle is that the traction load is distributed more evenly over the 4 wheels. This generally tends to improve the R/R_0 behavior, but there still remains a large variation in the overall performance in the R/R_0 behavior depending on the structure and control of a given AWD system. For AWD vehicles that are based on a RWD architecture, the tendency is to have understeer in the low lateral acceleration region (similar to a RWD vehicle) and then a transition to less understeer or even oversteer at larger lateral acceleration. For AWD vehicles with FWD architecture, the tendency is more like the FWD vehicle scenario but to a lesser degree. The similarity to either the RWD or FWD examples relies heavily on how a particular AWD system can transfer torque to the different wheels under a range of conditions.

As an ideal scenario, the differences between the steady state R/R_0 and accelerating and turning R/R_0 should be minimized to produce the most stable and maneuverable vehicle for all driving surfaces. When these R/R_0 characteristics overlay each other, the end vehicle result is similar line trace dynamics regardless of whether or not the vehicle is under acceleration. This yields a consistent and confident vehicle behavior during cornering by minimizing the amount of yaw change when the driver increases or decreases the throttle.

The AWD systems most capable of providing this type of optimal response under all driving conditions are those which have independent longitudinal and lateral torque biasing control. AWD systems with only longitudinal (front-to-rear) torque control have benefits for a limited sub-set of driving conditions, but lack the ability to provide optimal performance over a wide range of conditions or vehicle loading (without the assistance of electronic stability control). An AWD system with control of lateral (side-to-side) bias on a given axle such as that referenced by Shibahata (4) and Kunii (5) generates yaw moment that can be used to eliminate understeer over a wide range of conditions. Furthermore, the feed-forward

nature of this control allows a high level of refinement for a range of driving scenarios (before any intervention of stability assist programs are needed to rectify transient characteristics of lost traction and/or yaw stability). This produces both a maneuverable and stable driving result. This class of system may be called a Direct Yaw Control AWD System (DYC AWD System).

DIRECT YAW CONTROL SYSTEMS (DYC)

In comparing the variety of driveline systems discussed by Williams (1,2), it is not clear what types of system constructions provide the best performing, on-road characteristics over a wide range of conditions. In order to use the AWD system to its fullest extent, the fundamental requirement is that the yawing moment on the vehicle is favorably and directly affected by the AWD system. In particular, an optimal AWD system should be capable of real time, continuous drive torque distribution. The structural makeup of the system should produce: 1) a continuously variable, real-time side-to-side bias control on a given axle (preferably the rear axle so as not to disturb steering feedback), and 2) a continuously variable, real-time front-to-rear (longitudinal) distribution between front and rear axles so as to be able to control the driving load on the tires to allow more/less lateral adhesion. This type of AWD system can be called a Direct Yaw Control AWD System.

As a graphical representation of these two capabilities, refer to Figure 3 which shows that the DYC AWD system has two means by which to change the yawing moment of the vehicle. In the top image, it is possible to *directly* affect the yaw moment through differences in left and right wheel drive forces without affecting the tractive load on the front axle. This provides a yaw moment control mechanism which has a minimal impact on the overall lateral force balance between the front and rear axle. Since it does not change the front axle driving forces at all, the steering effort and road feedback are not affected.

The lower part of Figure 3 illustrates the front-to-rear (longitudinal) bias capability which can *in-directly* affect the yaw moment through the relationship of the tire force balance of the longitudinal and lateral directions. There are a variety of systems that use this mechanism (front-to-rear torque transfer only) to *in-directly* affect yaw from the AWD. Because the mechanism is through the tire longitudinal and lateral coupling, this affect is not as consistently effective as the direct yaw control mechanism mentioned above. It is, however, sufficient to affect gross understeer and oversteer behavior.