

Development of SH-AWD System using EPS Relative Steering Angle Signal

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ABSTRACT

The Super Handling-All Wheel Drive (SH-AWD) system uses the steering angle value to determine the proper left and right rear wheel torque distribution ratio to enhance vehicle handling response. Cost reduction in the application of the SH-AWD system is realized by (1) replacing the conventional stand-alone absolute steering angle sensor with an EPS resolver sensor, which determines the position of the EPS power assist motor, (2) applying integration to the change in the EPS motor position over time to yield a steering angle value relative to the initial steering rack position, and (3) using a new midpoint learning algorithm to determine the true steering angle value by calculating the difference between the initial steering rack position and the straight-ahead driving position. Through this process, a steering angle value relative to the initial steering rack position is acquired and is equivalent to the value that would be provided by an absolute steering angle sensor. To determine the straight-ahead steering position, a learning period is required during which the vehicle needs to travel a minimum distance every time the ignition key is turned on. To meet all existing system and CBU performance requirements during this learning period, two algorithms were created. First, a steering angle estimation algorithm substitutes as the true steering angle to allow SH-AWD to perform normal torque distribution operation. This algorithm uses two independent calculations to prevent excessive steering angle estimation, which would distribute more torque than necessary. Second, a new vehicle stability enhancement algorithm reduces the SH-AWD rear torque amount when an unstable driving event occurs. Using these algorithms, the SH-AWD system can achieve comparable performance by acquiring steering angle data from an EPS resolver sensor as opposed to a more costly absolute steering angle sensor.

1. Introduction

The SH-AWD system receives data from sensors and other control systems within the vehicle to determine a proper rear differential torque amount. The steering wheel angle represents the driver's intention to turn left or right and is used by the SH-AWD system to distribute torque to the left or right rear wheel for enhanced handling response.

Two types of steering angle sensors are commonly used in the industry. An absolute-type steering angle sensor permanently stores the straight-ahead reference position to immediately output the absolute position of the steering wheel when the ignition key is turned on, but this sensor is typically more expensive than a relative type sensor. Additionally, if the absolute-type stored midpoint is incorrect, such as after changes are made to the vehicle steering or suspension, the

midpoint value must be reset by a service procedure or else system malfunction may occur and could lead to customer complaints or additional warranty cost. A relative-type steering angle sensor has a simple low cost design but no permanent reference point to indicate the straight-ahead driving steering position, which is used as a reference point to determine the absolute position of the steering wheel to the left or right. Therefore, the relative-type sensor requires a midpoint learning algorithm to determine the straight-ahead position every time the ignition key is turned on. The midpoint learning algorithm needs the vehicle to travel a minimum distance to find the center steering position, which could delay the operation of some systems. The purpose of this research was to reduce the cost of the SH-AWD system by removing the stand-alone steering angle sensor and replacing it with the EPS system's resolver sensor, which is

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capable of calculating relative-type steering angle data. For vehicles that use EPS, the steering angle can be calculated without adding cost.

The influence of the steering angle value on the SH-AWD system operation was determined and objective performance requirements were created to evaluate the effectiveness of this new system configuration. The performance concerns of using the EPS relative-type steering angle signal were addressed as a part of this research.

2. Development Goals

The goal for the all-wheel-drive system's performance is to be consistent at all times, especially when climbing a steep hill or accelerating from a stop on a slippery surface. Changes made in the control system should be smooth so that the vehicle's behavior is not disturbed. Using a relative-type steering angle sensor creates two control states, where the true steering angle is initially unknown and where it is known after a learning interval. Therefore, new software algorithms are needed to enhance the performance of SH-AWD in this initial state. Once the midpoint learning is complete and the true steering angle is known, the EPS relative steering angle signal is identical to the absolute-type steering angle signal, so there is no impact to the SH-AWD system performance.

The SH-AWD system needs to meet the existing level for performance regardless of which control state the system is currently operating in, and it should operate in a way that is transparent to the driver. To achieve these targets, there are three new control algorithms that operate only during the initial control state: (1) a new midpoint learning algorithm

compatible with the EPS relative-type steering angle, which quickly and accurately finds the midpoint value to reduce the time spent in the initial control state; (2) an algorithm to allow torque vectoring of the rear axle to meet the system performance targets by estimating the steering angle value using other vehicle parameters; and (3) an algorithm to maintain vehicle stability while accelerating and turning to assist other vehicle control systems, which cannot perform their normal control until after the steering angle midpoint learning is complete.

3. EPS Relative-type Steering Angle Sensor

The EPS system uses a resolver sensor to monitor the electric power assist motor angle. Figure 1 shows the mechanical layout of the assist motor and resolver sensor. The EPS motor travels several complete revolutions while the steering rack moves from end to end.

The EPS resolver sensor uses electrical windings on a stator to measure the rotor position of the power assist motor. As shown in Fig. 2, the voltage relationship between the resolver windings determines the power assist motor angle. The motor angle value is integrated to calculate the total movement along the steering rack. The EPS system does not need to know the absolute position of the motor on the steering rack—only the driver's intention to steer left or right. The integrated resolver motor angle multiplied by the steering ratio results in a steering wheel angle value relative to the initial position of the power assist motor at the time that power was first applied to the system. Once system power is lost, the existing motor position is also lost and these values become unknown.

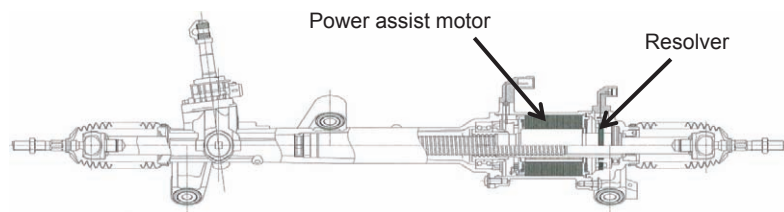


Fig. 1 Electric Power Steering rack structure

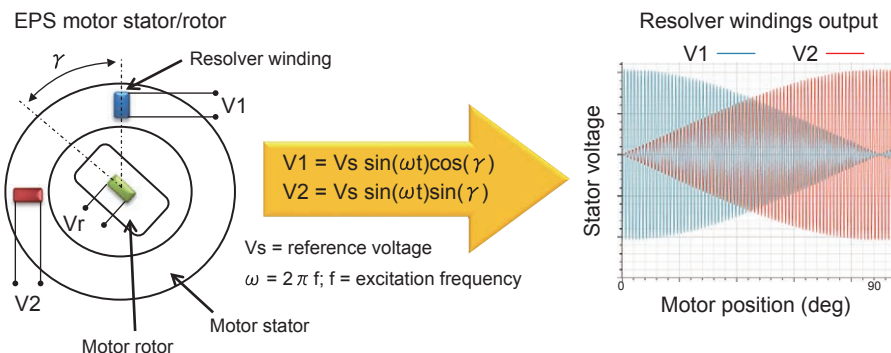


Fig. 2 EPS resolver sensor motor angle calculation

4. Midpoint Learning Algorithm

The midpoint learning algorithm is designed to take a steering angle value that has no reference point for straight-ahead driving and determine the amount of offset required to make that relationship known. Some relative-type steering angle sensors have built-in hardware that report when the steering wheel is in the straight-ahead position, in which case the midpoint learning algorithm must clarify if the wheel is truly at 0 degrees or at some multiple of 360 degrees. For the EPS relative-type steering angle, no such built-in hardware exists for the straight-ahead position, so a high accuracy algorithm is required. This algorithm can quickly determine that the vehicle is moving straight ahead and calculate the offset amount required to calibrate this position to 0 degrees.

To meet performance requirements, an absolute-type steering angle sensor must provide steering angle data at or above a required level of accuracy. To meet the same SH-AWD system performance requirements, the EPS relative steering angle signal must also achieve the same level of accuracy. To achieve this level of accuracy with a relative-type steering angle signal, many driving mode requirements were created. To allow for high accuracy and fast detection, two straight-ahead driving judgment calculations were used. The first judgment uses wheel speed requirements along with yaw rate and lateral G characteristic tables to judge that the vehicle is driving stable along a straight path. The second judgment uses different wheel speed requirements and two steering angle estimation algorithms (Eqs. 1 and 2)

that must be below a threshold amount. Figures 3 and 4 show the vehicle geometry parameters for steering angle estimation and the estimation accuracy achieved while driving on a predetermined winding road course.

$$\text{Steering angle by rear wheel delta rotation (deg): } \frac{|V_o - V_i| * WB * SR * 360}{(V_o + V_i) * TR * \pi} \quad (1)$$

$$\text{Steering angle by yaw rate and speed (deg): } \frac{WB * YAW * SR}{\text{Vehicle speed}} \quad (2)$$

Using these calculations alone resulted in midpoint accuracy of ± 6 degrees, with the worst case data

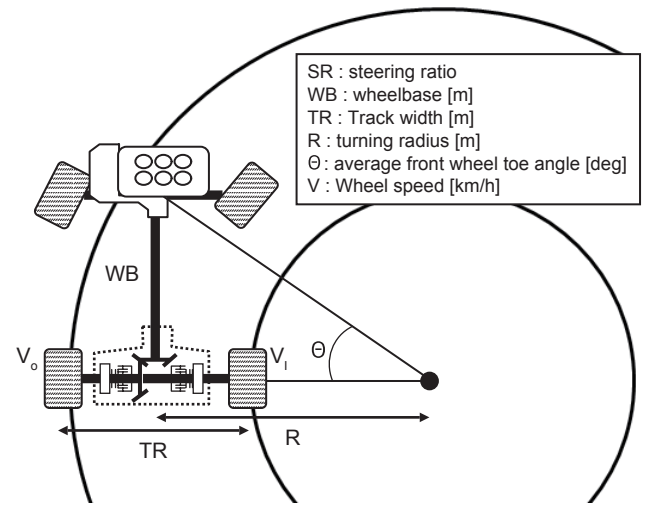


Fig. 3 Vehicle geometry parameters for steering angle estimation

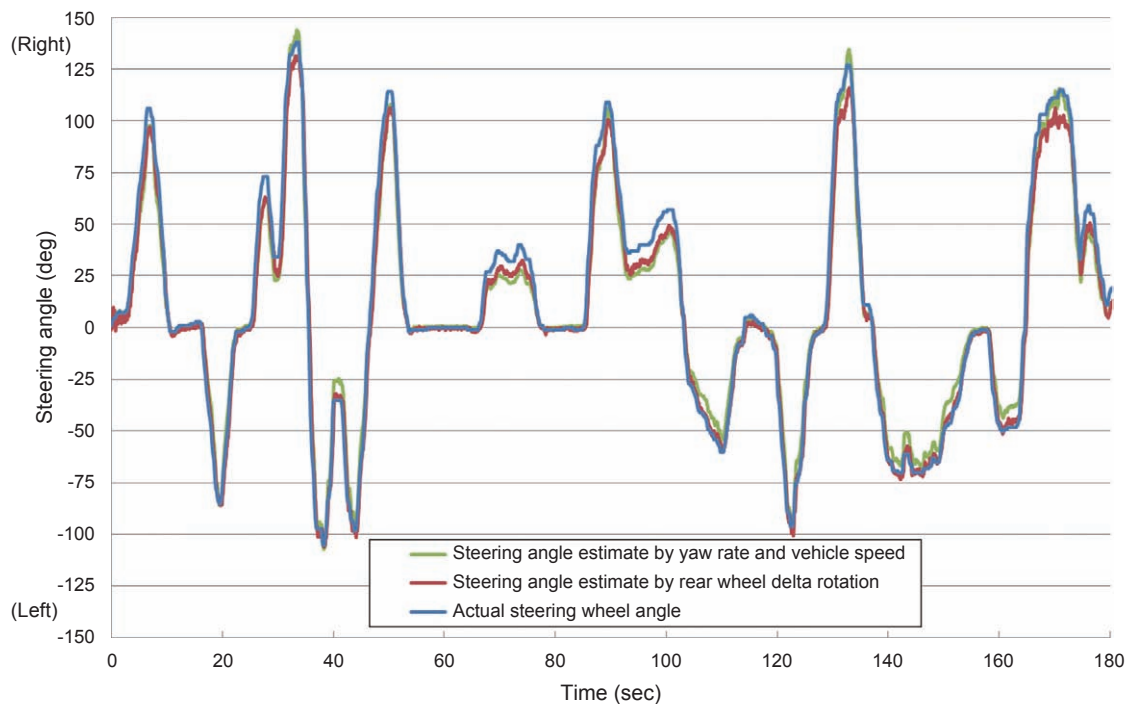


Fig. 4 Steering angle estimation accuracy

points occurring during extreme driving conditions. As shown in Fig. 5, the addition of requirements for a stable EPS steering angle value along with a one second averaging algorithm achieved results of ± 3 degrees for all driving situations. This level of accuracy meets the SH-AWD system design requirement. This calibration usually finishes within the first 400 m of driving under normal driving conditions, but can be shorter or longer based on the availability of a straight road.

The total error of the steering angle signal includes the midpoint learning algorithm error, the EPS system mechanical error, and the yaw rate sensor installation angle error. The EPS system mechanical components have a base amount of error regardless of steering rack position as well as error that increases toward both ends of the steering rack. The yaw rate and

lateral G sensor have an acceptable range for zero point accuracy in order to be used by the SH-AWD system. If both sensors are at the upper limit of acceptable range, the steering angle midpoint learning algorithm has a small amount of additional error. The total overall steering angle error is ± 8.4 degrees (see Fig. 6). The EPS steering angle signal measurement point is directly on the steering rack, rather than behind the steering wheel as with the stand-alone steering angle sensor. This removes up to 5 degrees of deflection that occurs within the steering column. Therefore, the total overall steering angle error of the EPS relative type and stand-alone absolute type are at an equal level, and no SH-AWD performance impact is introduced due to using the EPS relative steering angle signal.

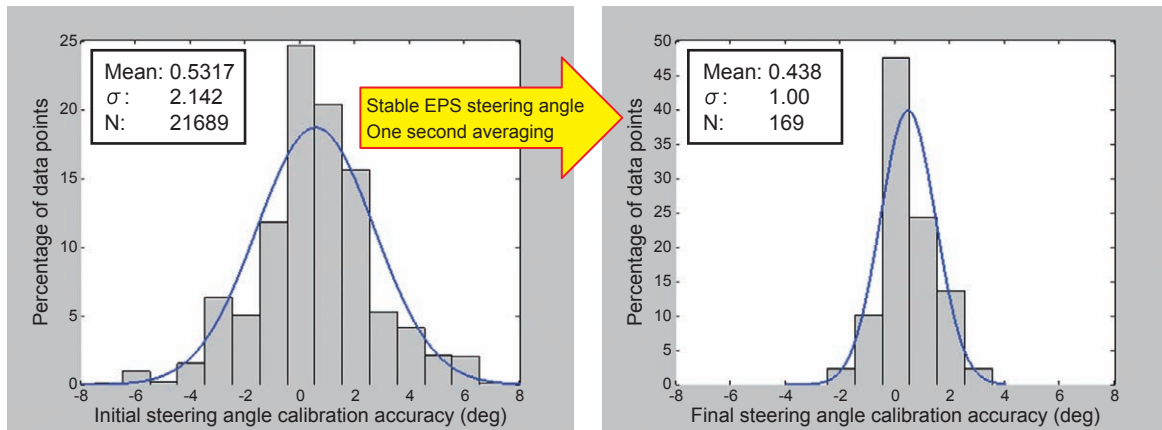


Fig. 5 Midpoint learning algorithm accuracy

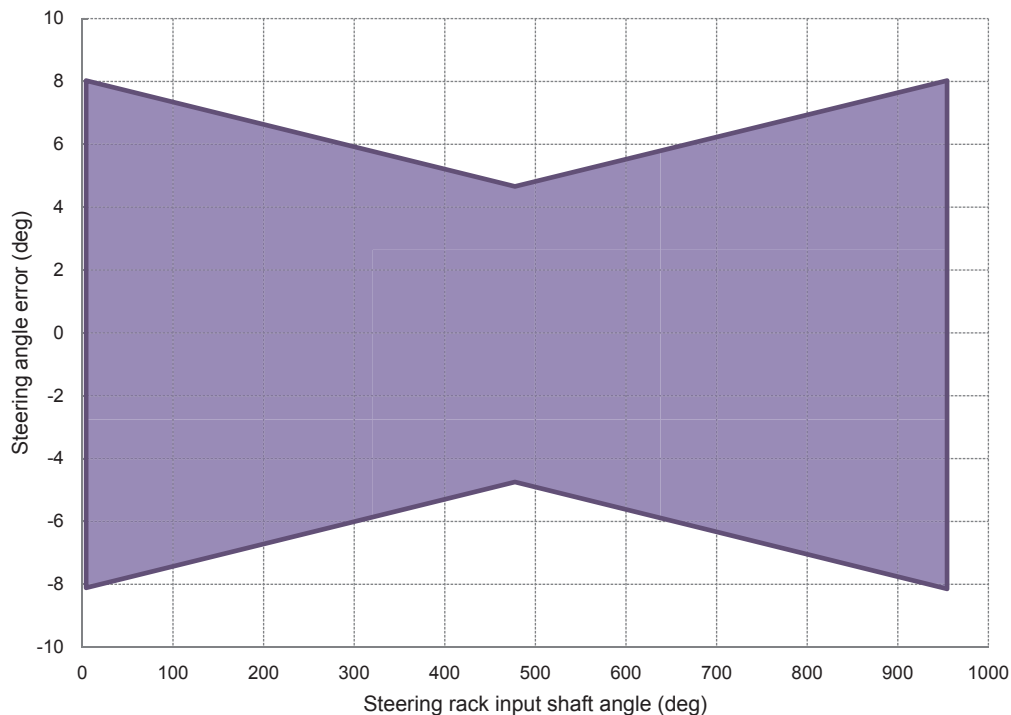


Fig. 6 EPS relative-type steering angle calculation error

5. Steering Angle Substitution

To achieve a SH-AWD system performance that is consistent and transparent to the driver, a substitute for the EPS steering angle value is required until the midpoint learning algorithm has finished, otherwise the SH-AWD will not be able to apply torque vectoring and vehicle performance will be reduced. The two steering angle estimation algorithms used for midpoint learning have very good accuracy for stable driving maneuvers, where the vehicle dynamics are linear. As shown in Fig. 7, as the driver operates the vehicle closer to the tire grip limit, the input relationships become non-linear and the steering angle estimation algorithms lose accuracy.

The design concept for steering angle substitution is to maintain the SH-AWD system performance during stable driving situations and prevent applying more rear torque than is normally distributed, which could lead to unstable vehicle dynamics. To achieve this concept, the estimated steering angle used for

SH-AWD control must be the same or lower in amplitude than if the system were using a calibrated steering angle sensor. The variables in the estimation calculations are different and, during certain driving maneuvers, one of the steering angle variables could become larger than intended, in which case the desired result is to use the other more accurate signal. Logic was made to selectively use the estimated steering angle value with the lowest amplitude and slope. This logic is effective at preventing a final estimated steering angle that is too large. During a transient maneuver it is possible for one steering angle estimate to suddenly decrease giving it the lowest amplitude, but by using the slope parameter, the signal switching does not occur until that signal stabilizes. This helps give the SH-AWD system consistent performance even during transient driving maneuvers near the tire grip limit. During unstable driving situations, one steering angle estimate can be a positive value and the other a negative value, in such case a final steering angle value of 0 degrees is used. Figure 8 shows the

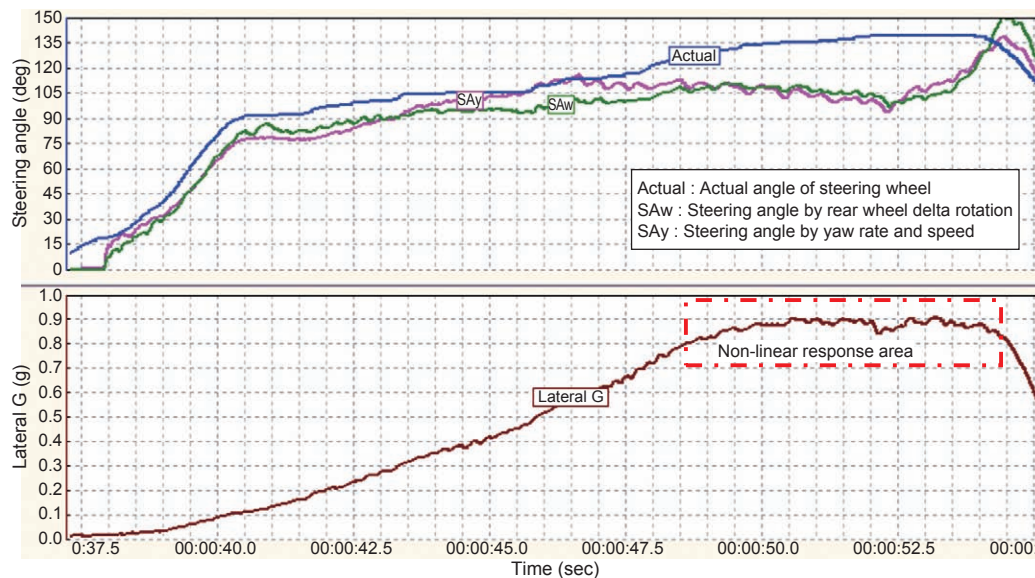


Fig. 7 Steering angle estimation accuracy versus lateral G

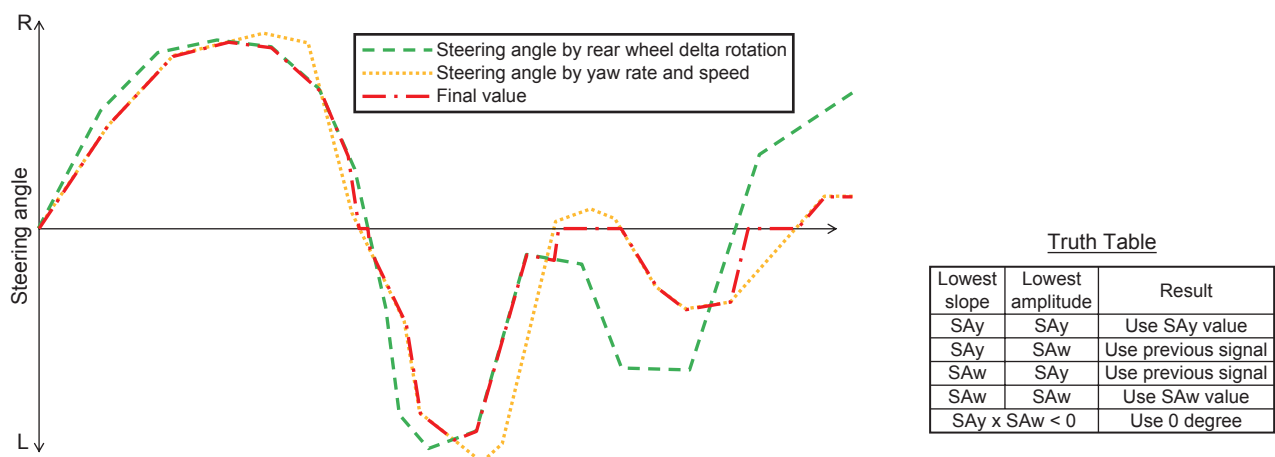


Fig. 8 Estimated steering angle signal selection logic

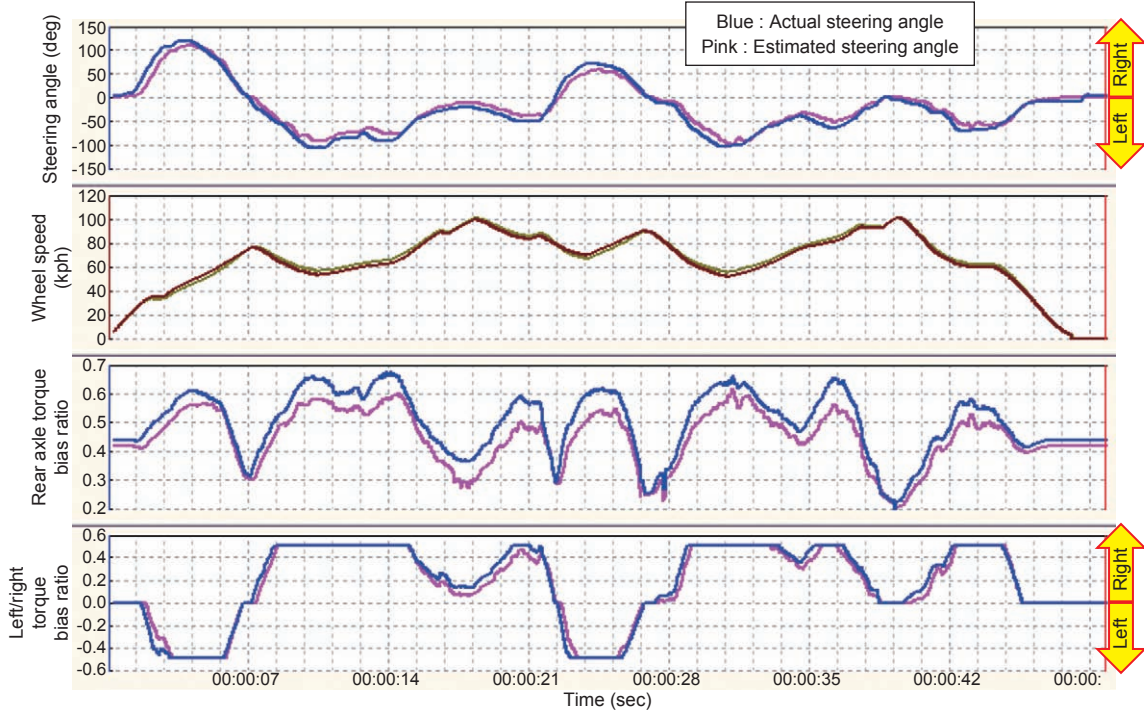


Fig. 9 SH-AWD system torque distribution change from estimated steering angle

operation of the estimated steering angle selection logic.

The change in SH-AWD system performance with the estimated steering angle was evaluated using hardware-in-the-loop simulation. The desired effect of using the estimated steering angle to allow torque vectoring to occur normally was achieved, but with slightly less rear torque and left/right distribution. As shown in Fig. 9, the effect on the front/rear torque distribution and rear axle left/right torque distribution yielded a worst case reduction of 10% compared to using the true steering angle value. The SH-AWD system performance using the estimated steering angle was evaluated by vehicle handling experts using the standard SH-AWD test courses and driving maneuvers. The SH-AWD system performance requirements were met and the system was judged acceptable. This amount of torque reduction was judged by vehicle handling experts to be similar in feeling to a slight change in road surface grip, which is typical under normal driving conditions.

6. Vehicle Stability Enhancement

Other control systems in the vehicle have limited performance capability while calculating their steering angle midpoint. During this time, the driver could experience an unstable driving situation that would normally be stabilized by one of these systems. Therefore, each control system that affects the vehicle dynamics must be capable of regulating its own performance to maintain stability during the midpoint learning time. When the absolute steering angle sensor

is applied, this performance regulating function is not needed. However, for the SH-AWD system to apply the EPS relative steering angle signal, an algorithm is required to determine when and how much to regulate performance. When accelerating and turning on road surfaces with a low coefficient of friction (low μ), the SH-AWD system can cause oversteer to occur if too much rear axle torque or left-to-right bias torque is applied. To enhance the stability in this situation, the SH-AWD system limits the rear axle torque distribution when an unstable driving event is detected (see Fig. 10). The SH-AWD system uses a normalized wheel slip calculation to determine vehicle instability and a yaw rate error calculation to determine that the car is oversteering. Using this information, the SH-AWD system sets an upper limit for the rear axle torque to stabilize the vehicle.

Understanding the speed relationship between all four wheels is critical to understanding how to detect when too much torque is applied and how to correct it. As shown in Eqs. (3)-(5) and Fig. 11, a normalized wheel slip calculation was made by comparing the wheel speed relationships between left and right along with front and rear. This wheel slip calculation has a stable driving region under which the data for all normal driving situations fall, and any data beyond this region occurs only when a vehicle loses traction.

$$\text{Left/Right Speed Delta: } V_{SLIP1} = (|V_{FL} - V_{FR}| - |V_{RL} - V_{RR}|) \quad (3)$$

$$\text{Front/Rear Speed Delta: } V_{SLIP2} = (|V_{FL} - V_{RL}| - |V_{FR} - V_{RR}|) \quad (4)$$

$$\text{Normalized Wheel Slip: } MAX(V_{SLIP1}, V_{SLIP2}) - \text{StableRegion} \quad (5)$$

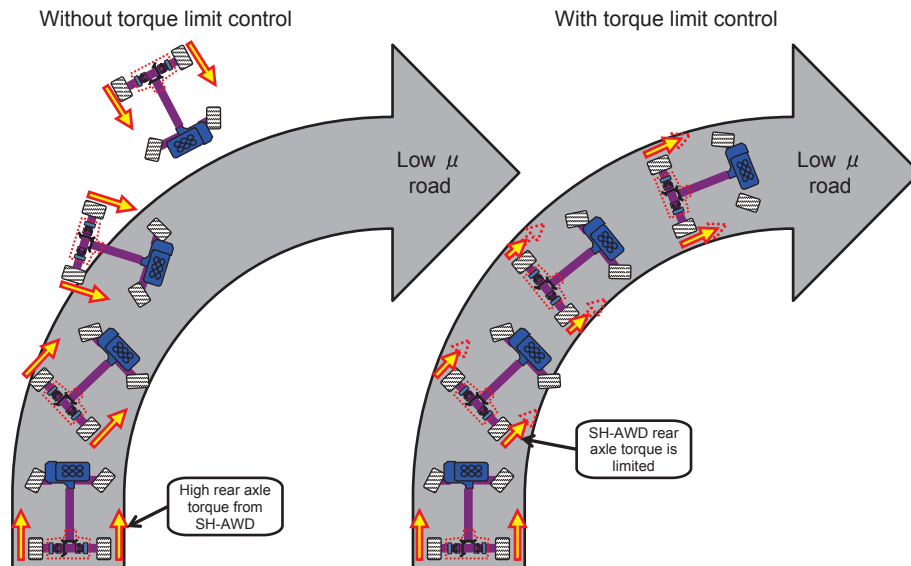


Fig. 10 SH-AWD vehicle stability enhancement operation concept

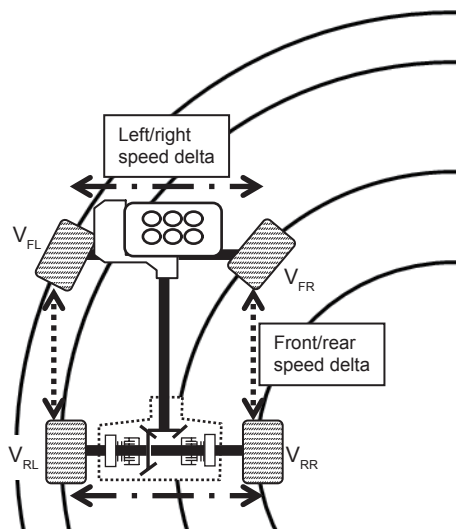


Fig. 11 Normalized wheel slip calculation

Figure 12 shows the normalized wheel slip calculation relationships during a 5 m radius turn (which has a very high speed difference between each wheel) and shows the ability of this logic to differentiate between wheel slip and tight turning. Initially the vehicle is able to do a 5 m radius turn while maintaining grip with the road surface, but as vehicle speed increases the tires eventually lose grip and the vehicle becomes unstable. The SH-AWD system removes torque from the inside rear wheel while cornering and distributes it to the outside rear wheel. This creates a situation where the inside and outside rear wheel increase speed at different rates when they lose grip.

If the vehicle loses traction driving straight, the steering angle is not needed by other systems to stabilize the vehicle; therefore, a yaw rate error algorithm was created inside the SH-AWD system to

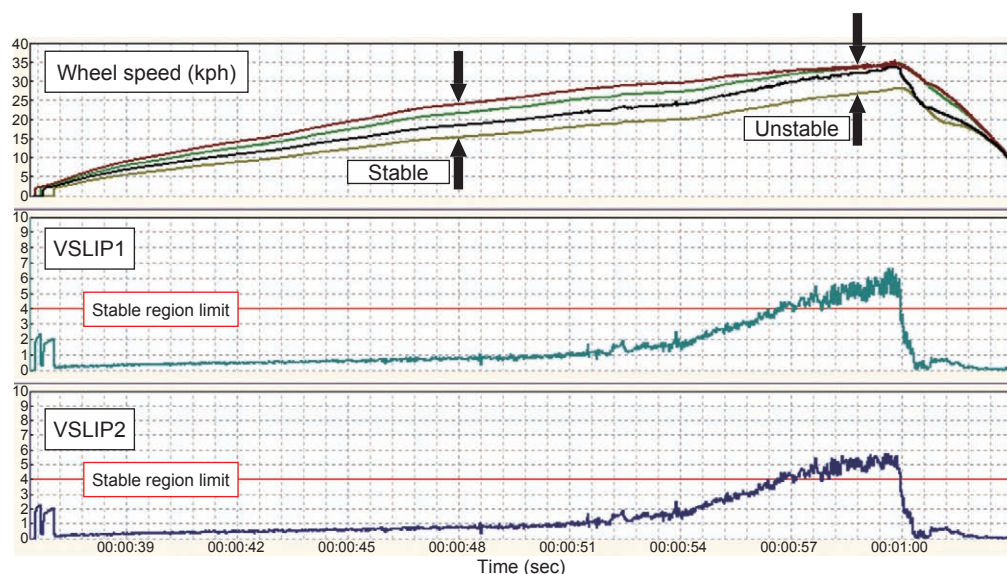


Fig. 12 Normalized wheel slip calculation during an accelerating 5 m radius turn

detect instability only while turning. The yaw rate error algorithm works with the normalized wheel slip calculation to determine when the SH-AWD system should limit the rear torque output. As shown in Eqs. (6) and (7), the actual yaw rate of the vehicle is compared to an estimated yaw rate calculated using the vehicle speed and lateral G sensor to determine the yaw rate error amount.

$$\text{Estimated Yaw Rate (deg/s)} = \frac{\text{Lateral } G \left(\frac{m}{s^2}\right) * 180}{\text{Vehicle speed} \left(\frac{m}{s}\right) * \pi} \quad (6)$$

$$\text{Yaw Rate Error} = |\text{YAW} - \text{Estimated YAW}| - \text{StableRegion} \quad (7)$$

During stable driving maneuvers, the actual and estimated yaw rates are nearly the same with a small amount of inaccuracy that decreases as the vehicle speed increases. As shown in Fig. 13, this inaccuracy is taken into account in order to create a stable driving region for the estimated yaw rate. When the yaw rate error goes beyond the stable driving region, the vehicle is oversteering and the SH-AWD system needs to limit the rear axle torque.

The SH-AWD system has several activation requirements before limiting the rear axle torque in order to prevent system misoperation. Situations such as driving on gravel or bumpy roads may cause the stability algorithm to temporarily go beyond the stable region, even though the vehicle is actually stable. To correct for such situations, the instability must be judged for a minimum time and the wheel speed, yaw rate, and lateral G sensor values must be within an allowable range. Using these conditions, the torque limit misoperation was eliminated.

To determine the torque limit amount, the normalized wheel slip calculation and the yaw rate error calculation are combined to create an instability index value. This value represents how unstable the

vehicle is in a range from 0 to 10, with 0 representing good stability and 10 representing very unstable driving. The SH-AWD system normally reduces the total rear axle torque as vehicle speed increases; therefore, if instability occurs at higher speeds, the torque limit amount needs to be lower to achieve the stabilizing effect. The torque limit starts at a default amount and is scaled by the instability index value and vehicle speed. As shown in Fig. 14, as the instability index value increases, the torque is limited to a lower value because more stabilization is needed.

To evaluate the torque limit control, the performance was compared to a vehicle using an absolute-type steering angle sensor with all driver aids enabled on both vehicles. The torque limit control is only needed during midpoint learning, so the vehicle with the EPS relative-type steering angle was only evaluated in this condition. The driving modes that

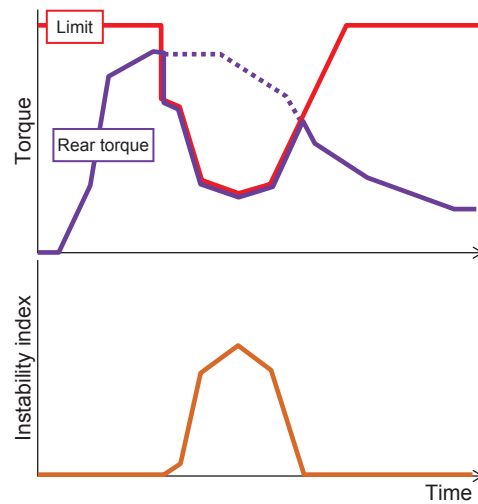


Fig. 14 Torque limit based on instability index value

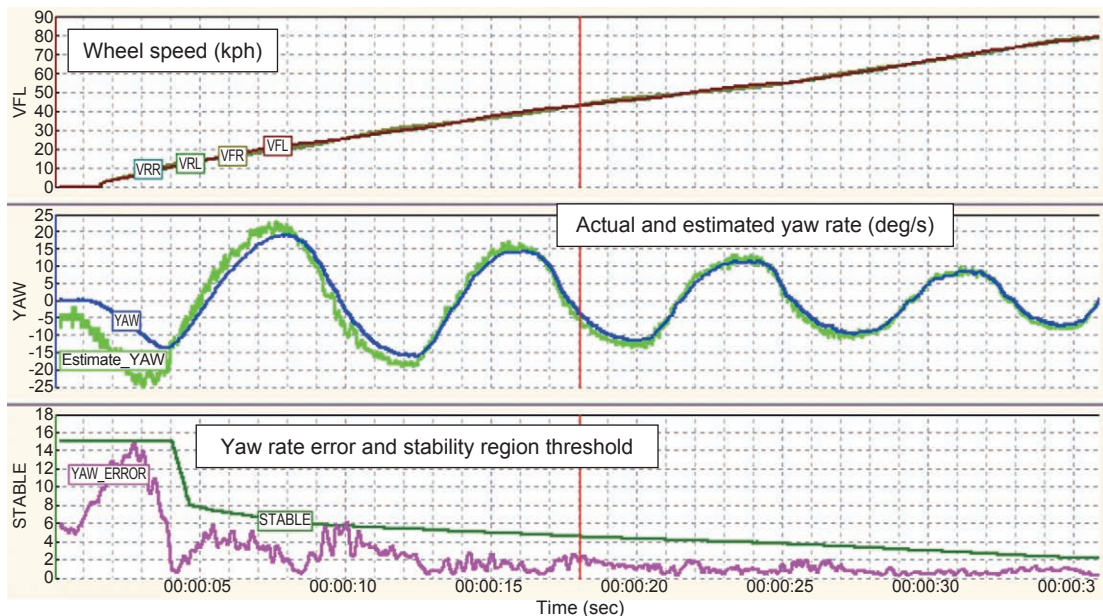


Fig. 13 Yaw rate error calculation

needed torque limit control the most were a slalom or constant radius turn on snow or ice as well as driving on a snow-covered winding road.

Driving aggressively on these courses with an absolute-type steering angle sensor results in other control systems reducing the engine torque or selectively applying the brakes to stabilize the vehicle as necessary. The vehicle using the EPS relative-type steering angle does not have the same level of capability from the other control systems during midpoint learning. The SH-AWD system torque limit function redirects torque to the front axle when instability is detected, which also maximizes the benefit of the other control system capabilities that are available. The driver was easily able to maneuver through these courses in both vehicles with a high level of safety margin. The driver feeling difference between the two vehicles is small enough that changes in the road surface conditions have a similar effect. Given the opportunity for a back-to-back test, most people would not be able to perceive any difference. With this level of performance, the SH-AWD system can apply the EPS relative steering angle signal and all vehicle stability performance requirements are achieved.

7. Conclusion

The EPS relative-type steering angle sensor can be used with the SH-AWD system to meet or exceed performance requirements. A new steering angle midpoint learning algorithm was created to work with the hardware configuration of the EPS system. A steering angle substitution algorithm allows the SH-AWD system to maintain consistent performance capability during the midpoint learning time. The vehicle stability enhancement algorithm allows the SH-AWD system to determine when too much rear axle torque is applied for the current road surface conditions to stabilize the vehicle. With this new logic, using the EPS relative-type steering angle reduces overall system cost and the difference in performance compared to an absolute sensor should be imperceptible.

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