

ENHANCEMENT OF VEHICLE STABILITY BY CONTROLLING THE FRONT BRAKES AND ENGINE TORQUE

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ABSTRACT

For the progress of vehicle safety, enhancement of active safety performance is as important as crash safety performance.

In emergency situations, it is very difficult for an ordinary driver to stabilize the vehicle because steering, braking, and/or other operations in this situation change the vehicle behavior suddenly.

From this point of view, enhancement of vehicle stability is very important for active safety. HONDA has developed an active safety system called **VSA** (Vehicle Stability Assist) based on expanding the usual active safety system, **ABS** (Anti-lock Brake System) and **TCS** (Traction Control System).

VSA controls front wheel brakes and engine torque to stabilize the vehicle by comparing yaw rate of the vehicle with the reference value calculated from lateral acceleration and vehicle speed, and the driver's intention estimated from steering angle.

INTRODUCTION

In a broad sense, active safety performance is related to all aspects of vehicle performance in terms of improving vehicle safety. Vehicle motion stability in particular is said to be closely associated with active safety from the perspective of accident avoidance.

Chaotic vehicle behavior caused by environmental, vehicle and human factors makes it difficult for an ordinary driver to control the vehicle. This is particularly evident when operating a vehicle under tense circumstances such as when attempting to avoid an accident.

For example, there are numerous cases where accidents could not be prevented because sudden steering, braking, and/or other evasive actions changed the vehicle behavior abruptly, making it impossible to steer the vehicle. From this point of view, there are hopes for new driving assistance technology to support driver operations from the vehicle side during critical behavior.

HONDA feels that it is extremely important in terms of active safety to have the vehicle detect when behavior becomes unstable due to evasive actions or sudden changes in the environment, etc., and to suppress any resulting changes in behavior. This thinking has led to the

development of an original **VSA** (Vehicle Stability Assist) system based on expanding the conventional **ABS** (Anti-lock Brake System) and **TCS** (Traction Control System). This **VSA** system suppresses vehicle sliding at all times even when not braking or accelerating to ensure that drivers are able to control the vehicle.

This paper describes the concept, principle, system configuration, control outline and effects of the **VSA** system. In addition, an original tire model is also introduced in the section concerning the principles of **VSA**.

BACKGROUND

Recently, typical active safety devices such as **ABS** and **TCS** are becoming standard equipment. However, both **FaAA** (Failure Analysis Associates INC.) and **NHTSA** have reported that "while the installation of **ABS** has reduced the number of multiple-car accidents in the U.S., single-car accidents have on the contrary increased." This is thought to be largely due to a lack of understanding on the part of the driver and insufficient PR by the manufacturer, thus giving the driver the false impression that **ABS** makes it possible to exceed physical limits and making the driver overconfident and reckless. However, there are also other causes, and these reports suggest that there is still some room for improvement in these systems.

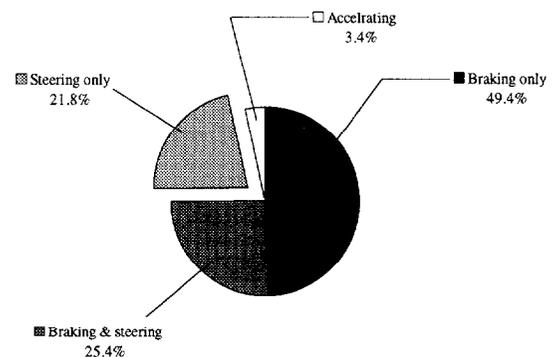


Figure 1. Pre-accident evasive operation(s) (2673 cases)

The **ABS** and **TCS** systems suppress peripheral slipping of the tires during critical braking and accelerating, thus ensuring sufficient tire lateral force. In other words, these driving assistance systems increase the driving margin with respect to lateral vehicle motion during critical braking and accelerating. However, these systems are essentially limited in that:

"They do not function when the driver is not stepping on the brake or accelerator."

Active safety technology must be developed based on elementary, time-consuming research such as analyzing basic factors causing accidents and driver behavior when accidents occur. Thus, conclusions cannot be reached in a short time. However, it is clear that **ABS** and **TCS** have the above-noted limitation, so technology that suppresses unstable vehicle behavior even when attempting to evade an accident using only steering wheel operations is necessary.

VSA DEVELOPMENT CONCEPTS

Under these circumstances, **VSA** was developed from the following two points with the aim of significantly enhancing the active safety performance of conventional **ABS** and **TCS**.

(1) Ensuring that the driver can control the vehicle by stabilizing vehicle behavior through vehicle sliding, etc., even when neither braking nor accelerating is being performed.

(Adding new functions)

This point consists of working to stabilize vehicle behavior under various conditions by resolving the above-noted essential limitation with **ABS** and **TCS**.

(2) Further, working to enhance **ABS** and **TCS** performance by utilizing vehicle sliding and other measured information.

(Enhancing the performance of existing functions)

In other words, controlling the tires so that they do not slip in the peripheral direction not only ensures sufficient lateral force but also actively stabilizes vehicle behavior, etc. This works to enhance the essential safety performance (stabilizing vehicle behavior) of **ABS** and **TCS**.

VSA development was based on the following three basic concepts.

1. The system should be simple and offer high reliability.

Reliability is a basic performance aspect of safety devices. Particularly for the **VSA** that aims to improve driver control, lack of reliability equals a critical loss of function. Therefore, the hardware configuration was made as simple

as possible from the viewpoint that simplification of the structure is one of the most basic methods of ensuring reliability.

2. The system should allow wide spread adoption.

It was thought that creating an easily affordable system would be a first in terms of proposing a new safety technology for a vehicle-based society. In addition, from the perspective of wide-spread adoption, the initial development assumed application in front-wheel-drive vehicles which have become the most common drive system in recent years.

3. The system should not interfere with the driver's operations or adversely affect the steering feeling.

In contrast to the basic stance of "how vehicles should be with respect to people," this system was based on the view that "the main force behind driving should be the driver." Therefore, this system places priority to the "person" without adversely affect the steering feeling by functioning only when the driver actually needs assistance.

SPIN & DRIFT OUT

The longitudinal and lateral forces exerted by the tires determine vehicle motion, but these forces possess saturation characteristics. On the other hand, since the centripetal force required for turning is proportional to the square of the speed, the vehicle motion limits are dependent on the frictional limits of the tires.

All four wheels do not generally reach these frictional limits at the same time, and it is more common for either a front wheel or a rear wheel to reach their frictional limits first. Therefore, the phenomenon of unstable vehicle posture is broadly divided into instances where the front wheels reach their frictional limits first (the vehicle drifts toward the outside: drift out) and instances where the rear wheels reach their frictional limits first (the vehicle spins toward the inside: spin).

Which of the four wheels reaches its frictional limit first depends on various conditions such as the road condition and the vehicle speed. However, slipping of the tire essentially generates the tire force, so acceleration and deceleration produce vehicle spin and drift out. For example, if excessive driving torque is applied to a front-wheel-drive vehicle, causing the front wheels to spin, the front wheels reach their limits first when turning and the vehicle drifts out.

PRINCIPLE OF VSA

According to Reference (2) and other sources, controlling the traction of the each wheel can mitigate spin and drift out. Methods of controlling the traction of each

wheel include applying driving torque as mentioned in the above Reference, and applying braking torque to generate negative slip. However, if driving torque is automatically applied, the vehicle may accelerate against the driver's will, so the driving torque must be distributed. Therefore, this paper looks at stabilizing vehicle behavior by applying braking torque.

When theoretically analyzing vehicle behavior, it is first necessary to analytically consider the force exerted on the tires. This is often done using Fiala's theory, but this research introduced an original method to simplify the calculations in consideration of application to real-time simulations and other purposes. (This method is referred to here as the λ -METHOD.)

Figure 3. shows the results of calculating the manner in which peripheral slipping of the tires while turning affects the vehicle in the longitudinal and lateral directions using this method. This shows that the results calculated using the above-noted theoretical method match closely with the actual measured data.

This calculation method calculates the frictional force vectors acting on the wheel by transforming the relationship between the slip of the vehicle and the coefficient of friction (generally called the $\mu - \lambda$ characteristic) into a planar slip vector. (Figure 2.)

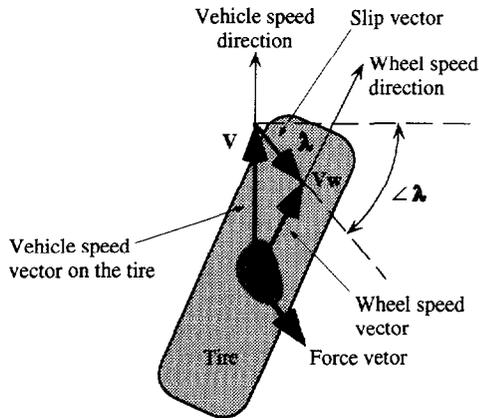


Figure 2. Vehicle speed, wheel speed, slip and force vectors.

The planar slip vector (λ) of the tire is:

$$\lambda = (\mathbf{Vw} - \mathbf{V}) / \max (|\mathbf{V}|, |\mathbf{Vw}|) \quad (1.)$$

and the force (\mathbf{f}) acting on the tire is thought to generate the "size of the slip quantity function in the slip direction over the plane".

That is to say, the force (\mathbf{f}) is expressed by the following equation:

$$\mathbf{f} = \mu (|\lambda|) \cdot \mathbf{Mg} \cdot \lambda / |\lambda| \quad (2.)$$

(Here, \mathbf{Vw} indicates the tire peripheral speed vector, \mathbf{V} the vehicle speed vector on the tire, and \mathbf{Mg} the vertical load. Also, in the equations used in this paper, vectors are indicated by thick characters, and scalar by thin characters.)

Here, the wheel peripheral speed is controlled by braking, so the wheel peripheral speed is K times ($0 \leq K \leq 1$) the body speed.

$$|\mathbf{Vw}| = K \cdot |\mathbf{V}| \quad (0 \leq K \leq 1) \quad (3.)$$

Obtaining the frictional force when the wheel speed skids at the slip angle (α) with respect to the body speed results in the following equation.

$$\angle \mathbf{Vw} - \angle \mathbf{V} = \alpha \text{ (Wheel slip angle)} \quad (4.)$$

At this time, λ is:

$$|\lambda| = \sqrt{(K \cdot \sin \alpha)^2 + (1 - K \cdot \cos \alpha)^2} \quad (5.)$$

$$\angle \lambda = \arctan ((1 - K \cdot \cos \alpha) / K \cdot \sin \alpha) \quad (6.)$$

Therefore, the coefficient of friction (μ_x) in the longitudinal direction with respect to the vehicle speed is:

$$\mu_x = \mu (|\lambda|) \cdot \sin (\angle \lambda) \quad (7.)$$

and the coefficient of friction (μ_y) in the lateral direction is:

$$\mu_y = \mu (|\lambda|) \cdot \cos (\angle \lambda) \quad (8.)$$

Here, the λ function of μ was simplified and calculated using the following equation:

$$\begin{aligned} \mu &= (\mu_p / \lambda_p) \cdot \lambda \\ &= (\mu_l - \mu_p) / (1 - \lambda_p) \cdot (\lambda - \lambda_p) + \mu_p \end{aligned} \quad \begin{cases} 0 \leq \lambda \leq \lambda_p \\ \lambda_p < \lambda \leq 1 \end{cases} \quad (9.)$$

(Here, μ_p is the maximum coefficient of friction produced by the road surface, and μ_l is generated using $|\lambda| = \lambda_p$. Also, μ_l is the coefficient of friction when the wheel is locked.)

Figure 3. shows that the calculated and experimental results match closely, indicating that the force exerted by the tires can be easily obtained using the λ -METHOD even when turning with heavy braking that causes the wheels to lock.

Figure 3. indicates that the lateral coefficient of friction can be adjusted by controlling the above-noted K value, that is to say the wheel peripheral speed with respect to the body speed. Also, since this K value can be controlled in the range of 0 to 1 by applying the brake, this means that applying the brake to control the peripheral slipping of the wheel can control the lateral friction coefficient.

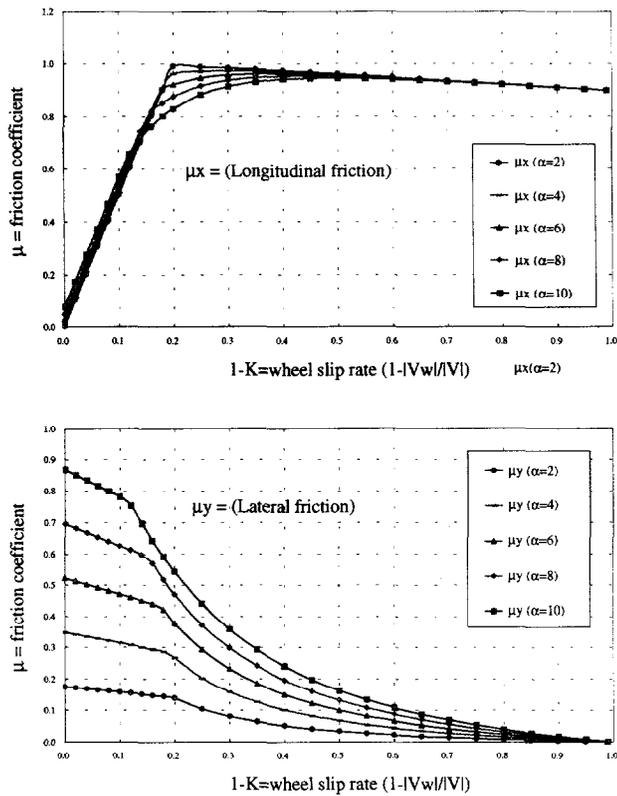


Figure 3. $\mu - \lambda$ characteristic.

Figure 4. shows rough calculations of the effects on vehicle rotating motion when the brake is actually applied to one wheel.

This figure shows the calculated effects of braking force on vehicle rotation when **Figure 3.** is calculated for all four wheels and the K value of only one wheel is shifted in the range of 0 to 1 with the K value for the other wheels set to 0 (that is to say when braking is performed for only one wheel). The actual results differ somewhat due to the respective wheel load and the position from the center of gravity of the tire, but τ_x , τ_y and τ are calculated using the following equations for reason of simplicity.

$$\tau_x = \mu x_1 - \mu x_2 + \mu x_3 - \mu x_4 \quad (10.)$$

$$\tau_y = -\mu y_1 - \mu y_2 + \mu y_3 + \mu y_4 \quad (11.)$$

$$\tau = \tau_x + \tau_y \quad (12.)$$

{Subscripts:

1: Outside front wheel, 2: Inside front wheel,

3: Outside rear wheel, 4: Inside rear wheel}

Here, τ_x represents the braking force component that works as the yaw moment, τ_y the lateral force component that works as the yaw moment, and τ the sum of these components. When τ is positive, braking generates a moment that rotates the vehicle to the outside; when τ is negative, braking generates a moment that rotates the vehicle to the inside.

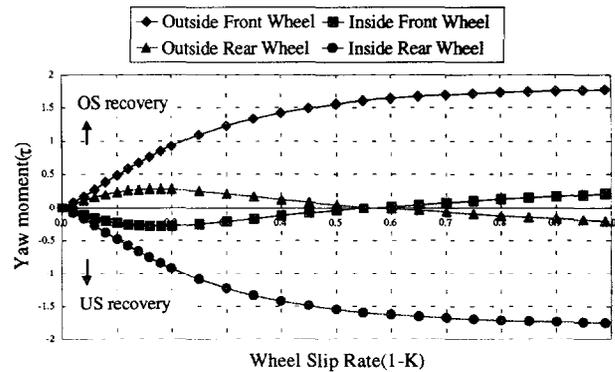


Figure 4. Effect of wheel braking on vehicle rotating

According to **Figure 4.**, outside front wheel braking suppresses the phenomenon where the vehicle attempts to rotate to the inside, and inside rear wheel braking suppresses the phenomenon where the vehicle attempts to rotate to the outside. This is the principle behind VSA that controls the vehicle posture by applying the brake to each wheel. **Figure 4.** also shows that the yaw moments of the inside front wheel and outside rear wheel braking forces change direction according to the wheel slipping. This is because the relationship between the direction of lateral force effect and the direction of braking force effect is reversed. For example, the braking force component of the outside rear wheel acts to point the vehicle toward the outside, but the drop in the lateral force component of the rear wheels acts in a direction that causes the vehicle to spin.

Dynamic model simulation

To confirm the above results dynamically, dynamic vehicle reaction was simulated using the 4-wheel vehicle planar motion model shown below.

(Note that the force exerted on the tires was calculated using the previously mentioned λ -METHOD.)

$$V_{wi} = R\omega_i \cdot A(\theta + \delta_i) \cdot U_x \tag{13.}$$

$$V_i = V_c + L_i \cdot \gamma \cdot A(\theta + \phi_i) \cdot U_y \tag{14.}$$

$$dV_c/dt = \Sigma A(\theta) \cdot f_i/M \tag{15.}$$

$$dX_c/dt = V_c \tag{16.}$$

$$d\gamma/dt = \Sigma L_i \cdot U_y^t \cdot A(-\phi_i) \cdot f_i/I_z \tag{17.}$$

$$d\theta/dt = \gamma \tag{18.}$$

Here,

- $R\omega_i$: Peripheral speed of each wheel
- L_i : Distance between the tire position and CG.
- Φ_i : Angle of the tire position relative to CG.
- δ_i : Actual steering angle of each tire
- γ : Yaw rate
- θ : Yaw angle
- f_i : Force exerted on the tires
- M : Vehicle mass
- I_z : Moment of inertia around the Z axis
- V_c : CG. speed vector
- X_c : CG. position
- U_x : x unit vector
- U_y : y unit vector
- U_y^t : U_y transposition vector
- $A(\theta)$: Rotation matrix of angle θ
(CG.: The center of gravity)

Figure 5. shows the vehicle locus, acceleration, speed and yaw rate when acceleration slip is generated on the rear wheels while turning as obtained with this model. These results show that operating the accelerator inadvertently while turning causes a rear-wheel-drive vehicle to spin. **Figure 6.** shows the simulation results when braking slip is applied to the outside front wheel in accordance with the vehicle sliding angle (β) under the same conditions as above. These results indicate that the vehicle can be turned without spinning even after applying sudden acceleration slip.

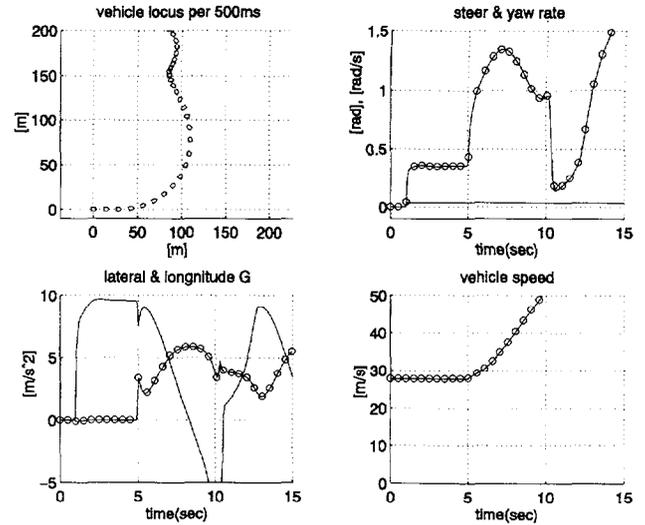


Figure 5. Simulation results (without front-brake control)

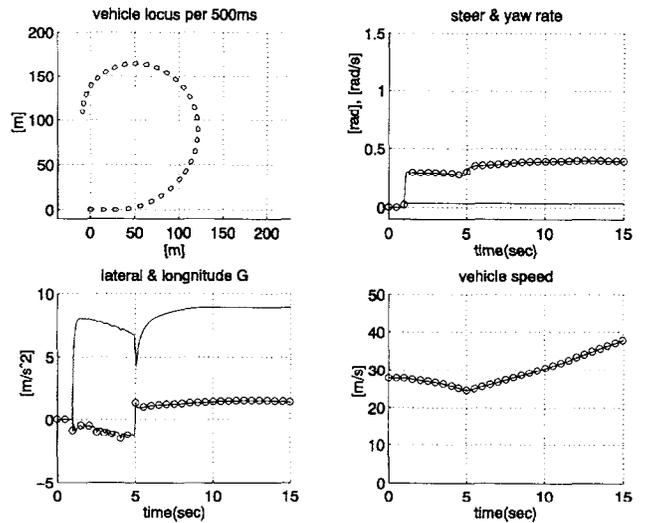


Figure 6. Simulation results (with front-brake control)

METHODOLOGY OF VSA CONTROL (2CH CONTROL SYSTEM)

According to **Figure 4.**, outside front wheel braking is effective at suppressing an increase in the angle of rotation, and inside rear wheel braking increases the angle of rotation. Spin refers to the phenomenon where the angle of vehicle rotation exceeds the revolution angle, so it could be said here that outside front wheel braking suppresses spin. This has also been verified with the above-mentioned dynamic simulation.

However, it cannot be said that drift out is suppressed simply by inside rear wheel braking. That is to say, the driver senses understeer (a feeling of insufficient turning) not simply when the vehicle does not face toward the inside, but instead when the driver wishes to direct the turning locus more toward the inside. Thus, most cases of understeer are when the driver wishes to turn with a smaller turning radius. (Hereafter, this condition is called “over-speed understeer”.)

Figure 7. shows the results of calculating how the turning posture and turning locus change during inside rear wheel braking. These results agree with those in **Figure 4.**, and show that while inside rear wheel braking effectively can increase vehicle rotation, it has little effect on the amount of lateral movement (equivalent to the turning radius).

In other words, even though braking suppresses changes in the vehicle posture, it is not very effective at reducing the turning radius.

Generally speaking, the resultant force exerted by the tires and the vehicle speed determined the locus of revolution. Thus, in order to reduce the turning radius, either increase the force exerted by the tires must be increased or the vehicle speed must be decreased. Realistically speaking, however, it is not possible to increase the frictional force exerted by the tires, so reducing the speed has a greater effect.

In contrast to this, it is also thought that “over-speed understeer” can be suppressed by reducing the vehicle speed by applying the brake to four or some wheels (“deceleration control”).

However, even if the speed is reduced, the deceleration has limit by the road friction, so it is not always possible to obtain the desired revolution locus. Further, the inability to negotiate a curve occurs easily on wet, snow-packed or other slippery road surfaces, so there is little reduction in speed in these cases.

In other words, unless the speed at which the next curve can be negotiated or where the driver is attempting to go can be predicted in advance, “deceleration control” cannot completely suppress “over-speed understeer”.

In addition, the fact that this system may give the driver the false impression of being able to negotiate an impossible curve must also be taken into account. Drivers are generally thought to apply the brakes when they determine that a curve cannot be negotiated. Therefore, it was felt that efforts should

be made to enhance safety by improving ABS performance rather than by “deceleration control”.

On the other hand, accelerator operations easily cause front-wheel-drive vehicles to drift out (“acceleration-understeer”), making TCS performance, or suppressing peripheral slipping of the tires, important for increasing behavior stability. This “acceleration- understeer” can be effectively suppressed by controlling front wheel slip independently for the right and left wheels by braking (“**Braking TCS**”).

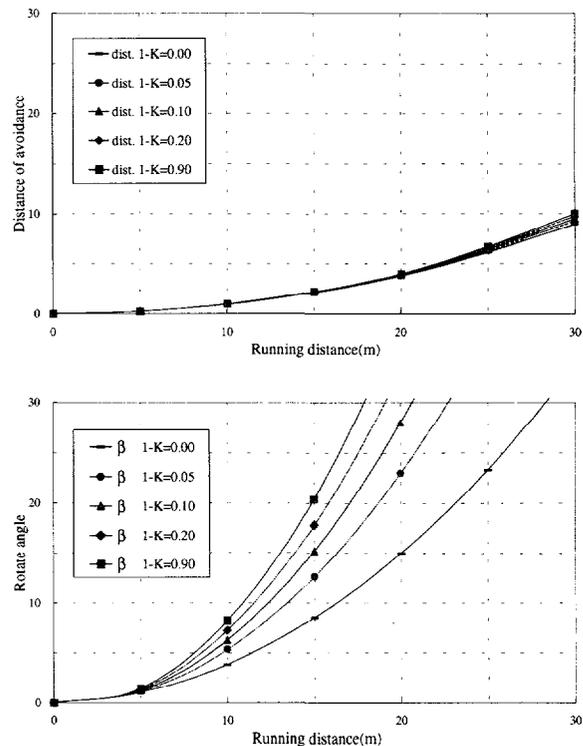


Figure 7. Effects of inside rear wheel braking on wheel reaction.

Summarizing the above points:

- 1) Vehicle spin can be suppressed by outside front wheel braking.
- 2) Inside rear wheel braking alone has little effect on suppressing drift out.
- 3) Assuming a front-wheel-drive vehicle, the desired effect can be achieved by applying pressure to only the front wheels with “**Braking TCS**”.

Therefore, controlling the braking pressure to the two front wheels and controlling the engine torque realizes a simple yet highly effective system for front-wheel-drive vehicle is one of the development concepts.

CONSTRUCTION OF THE VSA SYSTEM

Based on the above results, we constructed VSA by expanding the ABS and TCS with a yaw rate sensor and lateral accelerometer that directly measure the vehicle posture, a steering angle sensor and other sensors that estimate the driver's turning intention, and a hydraulic unit for independently pressurizing the front wheels. The ECU (Electrical Control Unit) was also expanded. (Figure 8.)

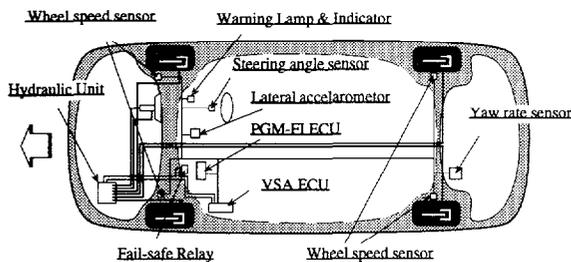


Figure 8. Construction of the VSA system.

The yaw rate sensor is a vibrating type whose reliability and accuracy have been enhanced for vehicle control. This yaw rate sensor is important because it sensor directly measures the vehicle's rotation, so a self-diagnosis circuit has been provided inside the sensor to improve system reliability. (Figure 9.)

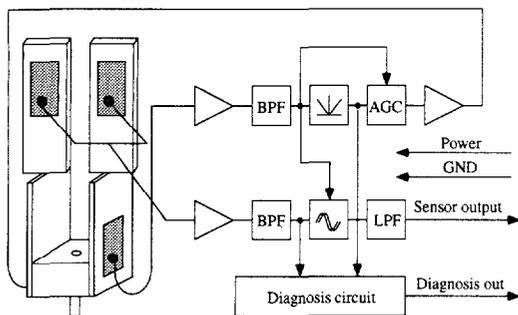


Figure 9. Yaw rate sensor

The lateral accelerometer and steering angle sensor are those used in the conventional TCS, but through FMEA (Failure Mode, Effect Analysis) there have been implemented inside the sensors to further improve reliability.

The VSA hydraulic units add a pressurizing unit onto the conventional ABS unit for a simple and compact structure. These two units have independent oil routes and are coupled via a pressurizing piston. The pressurizing units pressurize calipers that are linked to the ABS units by using pressurizing pistons and both the ABS pump and the VSA pump are driven one motor and one axle.

The pressurizing pistons transmit the higher of the pressures generated by the master cylinder or the pressurizing unit to the calipers. This allows braking to be performed according to the driver's intention even when the driver brakes suddenly during pressurization. Further, the pressure from the pressurizing unit is transmitted when vehicle behavior becomes unstable even during ABS operation or other braking, thus ensuring VSA operation. (Figure 10.)

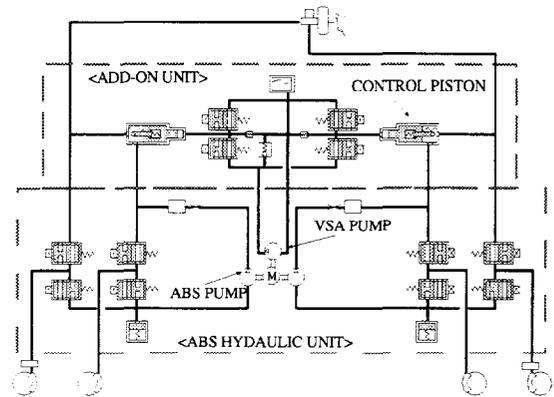


Figure 10. Hydraulic unit.

The ECU is comprised of a 16-bit main CPU (Central Processing Unit) and an 8-bit sub-CPU. Each CPU performs operations independently to ensure safety when making particularly important decisions. (Figure 11.)

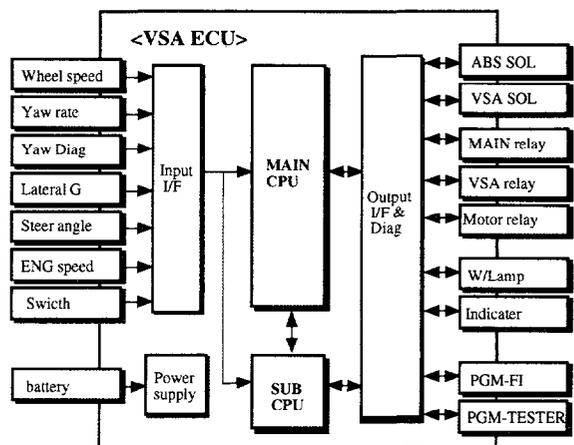


Figure 11. ECU block diagram

VSA CONTROL SOFTWARE

VSA control software is comprised of three blocks. The first of them is a control block that determines the vehicle posture from the yaw rate, lateral acceleration, steering angle, vehicle speed, etc. The second is the ABS/TCS control block that determines how to adjust the braking force based on the peripheral slippage of the wheels. And the third is an output control block that drives the pressurizing and ABS units based on the posture and braking pressure adjustment judgments, and at the same time communicates with the engine control unit to adjust the engine torque. (Figure 12.)

The vehicle posture is basically determined from the sliding angular rate of the vehicle. The centripetal acceleration while the vehicle is turning is proportional to the square of the speed and inversely proportional to the turning radius. In addition, the turning angle rate (revolution angular rate) as viewed from the inertia coordinate is proportional to the speed and inversely proportional to the turning radius.

Here, if the advancing speed and direction of the vehicle do not differ greatly from the vehicle direction, the revolution angular rate is obtained by dividing the centripetal acceleration, which is detected as a reaction force by the lateral accelerometer, by the speed.

On the other hand, the rotational motion of the vehicle is not restrained by the revolving motion, and is determined by the balance of the forces exerted on each wheel. The yaw rate at this time can be directly detected by sensing the Coriolis force generated with respect to the vibrating speed of the sensor trembler.

The turning angle rate does not greatly differ from revolution angular rate during normal turning. However, these rates differ greatly when the vehicle slides for whatever reason, making it possible to determine the vehicle posture by comparing the two.

In other words, the turning angle rate is greater than the revolution angular rate during spin, and this relationship is reversed during drift out. (Figure 13.)

On the other hand, when the speed is gradually increased from the condition of cornering at a constant speed, the condition where the steering angle must be increased is sometimes referred to as understeer, and the opposite as oversteer. Assuming cornering, the turning radius does not change so the revolution angular rate is proportional to the advancing speed. Therefore, this mode understeer (drift out) or oversteer (spin) can be judged by comparing the product of the steering angle and the speed with the actual yaw rate. The vehicle posture judgment block combines the above two judgment methods to comprehensively judge the sliding angular rate of sprung mass and the estimated driver's intent. At the same time this block also calculates the amount of sliding to be applied to the tires and the amount of engine torque adjustment based on this judgment.

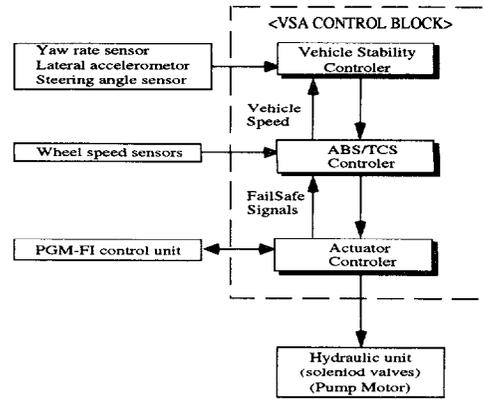


Figure 12. Control block diagram

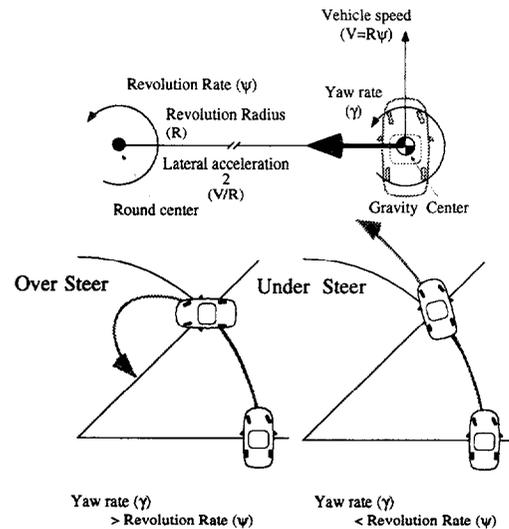


Figure 13. Yaw rate and revolution angular rate

The **ABS/TCS** control block compares the wheel speed with the body speed which is estimated from the wheel speed, and weakens the braking force if it determines that the wheels are likely to lock when the wheel speed is much slower than the body speed. This block also determines that the wheels are spinning and either lowers the engine torque or applies the brakes when the wheel speed is much faster than the body speed. Further, performance is enhanced compared to individual **ABS/TCS** operation by varying the **ABS/TCS** target slip according to the information from the posture judgment block. For example, normal **ABS** controls both rear wheels according to the wheel that slips the easiest. In contrast to this, **VSA** increases the deceleration rate and ensures stable braking by switching to 4CH independent **ABS** when there is judged to be sufficient rear lateral force margin when making a high-G turn. (**Figure 14**.)

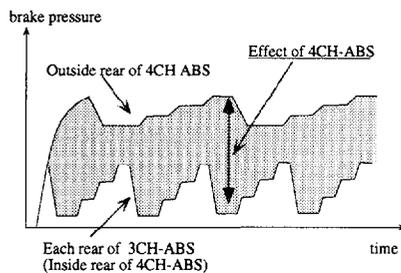


Figure 14. Effect of 4CH-ABS

In addition, if vehicle spin is detected during **ABS** operation, stable braking during a turn is ensured by increasing the target slip of the outside front wheel according to the degree of spin. This is an application of the principle shown in **Figure 4**.

This is because whereas **ABS** assumed that wheel slip less generally experience greater lateral force, it is sometimes easier to stabilize the vehicle by increasing the slipping depending on the vehicle balance. As for **TCS** control, when the generated yaw rate is small compared to the steering angle, the target slip is reduced, making it easier to generate lateral force. In addition, when vehicle spin is detected, **VSA** increase target slip of **TCS** so as not to interfere with acceleration based spin avoidance actions by the driver.

Further, even when the wheels are not slipping in the peripheral direction, if the vehicle posture judgment block determines that automatic braking is necessary, it signals the **ABS/TCS** control block which generates slipping on the brake side for one of the front tires.

The output control block finely controls the solenoid valves of the **ABS** and the pressurizing units and at the same time controls the hydraulic pumps and the hydraulic units to produce the slip requested by the **ABS/TCS** control block.

It is based on the results calculated by the **ABS/TCS** control block. In addition, the output control block also communicates with the engine control unit to perform the engine torque adjustment calculated by the **ABS/TCS** control block.

EFFECTS OF VSA

Figure 15. shows the results of simulating the amount of avoidance that can be performed without causing spin during open loop steering when there is no corrective steering by the driver. Actually, it is impossible to have absolutely no corrective steering when spin occurs as assumed by this simulation. However, this simulation shows that the **VSA** system roughly doubles the allowable avoidance amount under conditions of this type of limited simple steering.

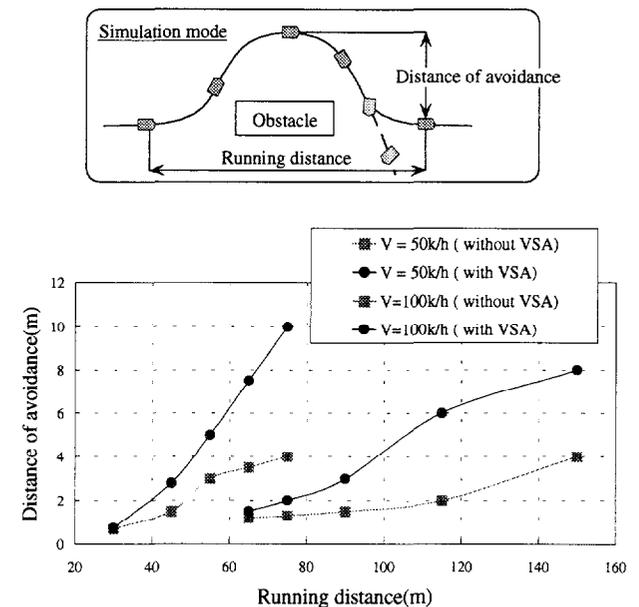


Figure 15. Capacity of crash avoidance. (simulation result)

Figure 16. shows the results of actual vehicle tests when the driver performed corrective steering. This figure shows the speed at which a double lane change can be performed on a low- μ road surface equivalent to a snow-packed road. These results differ from **Figure 15**. in that there is almost no difference either with or without **VSA** when corrective steering was performed by a skilled driver. However, it was found that the amount of steering operations through the double lane change decreased markedly with **VSA**. In addition, these test results also revealed that **VSA** made it possible for an ordinary driver to drive at roughly the same

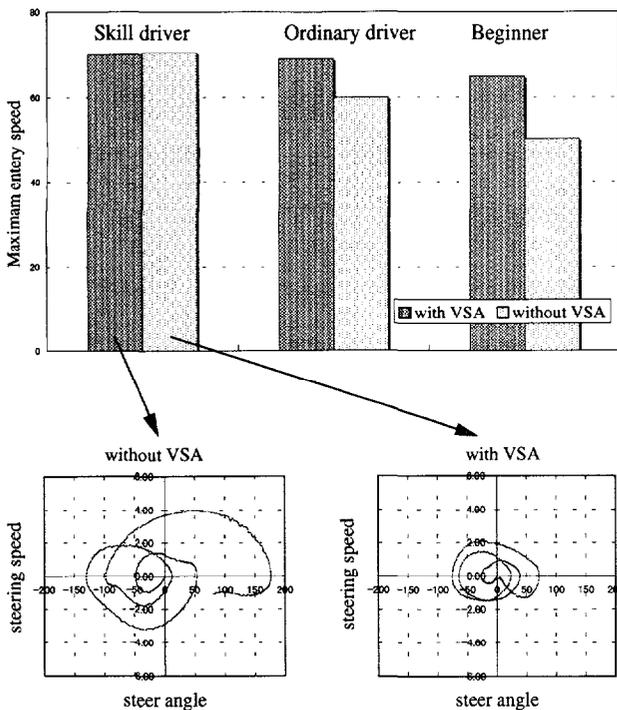


Figure 16. Lane-change performance: maximum entry speed and steering operation quantity (Vehicle test under ISO double lane change)

speed as a skilled driver.

Figure 15. and Figure 16. indicate that VSA assists driver operations to make driving operations possible during critical behavior as typified by emergency evasion. On the other hand, however, these results also proved that VSA does not raise the physical limits.

CONCLUSIONS

- (1) This paper introduced an original tire model, and confirmed that the VSA principle can be verified using the principle of this model (λ -METHOD).
- (2) A simple but highly efficient system was constructed by controlling the braking pressure to the front two tires and controlling the engine torque.
- (3) VSA was confirmed to assist driver operations during critical behavior through simulations and actual vehicle tests.

ACKNOWLEDGMENTS

We feel that VSA can help to improve vehicle safety by stabilizing the vehicle posture and assisting driver operations under conditions involving vehicle sliding where steering is ordinarily considered difficult.

However, the VSA system cannot raise the physical limits determine the produced frictional force and the inertia

of the vehicle, and the final route determination must be made by the driver. Further, current systems are unable judge whether it is physically possible to realize the driver's intentions.

We feel that it is important to enhance collision safety performance and at the same time perform further research and development concerning active safety to determine how far people can be supported from the vehicle side. On the other hand, we feel it is also important to carry out comprehensive activities to improve automobile safety including activities to educate drivers and encourage safe driving.

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