Improvement of Vehicle Dynamics by Right-and-Left Torque Vectoring System in Various Drivetrains*

Kaoru SAWASE* Yuichi USHIRODA*

Abstract

This paper describes the verification by calculation of vehicle dynamics improvement by means of a right-and-left torque vectoring system in various types of drivetrains. The amount of right-and-left torque vectoring needed for expanding the vehicle dynamics limit is also calculated, and suitable wheels to which the system should be applied for each drivetrain are evaluated. Application to the front wheels is more effective for the front wheel drive (FWD) vehicles, whereas application to the rear wheels is more effective for the rear wheel drive (RWD) and the all wheel drive (AWD) vehicles.

Key words: *Drivetrain, Vehicle Dynamics/Torque Vectoring, Torque Distribution*

1. Introduction

Since the 1980s, a range of vehicle dynamics control technologies has been released. Among them, direct yaw moment control with brakes, an effective technology for pro-actively preventing accidents, has become widely used today. In 1996, the world's first vehicle with a right-and-left torque vectoring type direct yaw moment control system was developed and released by the authors(1). The system directly controls the yaw moment acting on the vehicle regardless of whether the vehicle is accelerating or decelerating by transmitting torque between the left and right wheels. This feature improves cornering performance at all stages, from normal to critical driving(2).

Following on from this system, various torque vectoring systems have been proposed(3)(4). There have been a number of reports on improved performance of vehicle dynamics on AWD and RWD vehicles by applying a torque vectoring system to the rear wheels. However, there have been few reports on the effects of a torque vectoring system applied to the front wheels of AWD vehicles or to the rear wheels of FWD vehicles(5). Furthermore, there has been no report on a possible method for setting up the maximum vectoring torque of a torque vectoring system.

This paper first discusses a range of themes related to the right-and-left torque vectoring system, starting with its functions, and its applicability that even includes non-driving wheels such as the rear wheels of FWD vehicles. The paper then identifies the impact of the system on the vehicle dynamics limit and how to calculate the limit under impact. Then, using the calculation method, the vehicle dynamics limit is evaluated for when the system is introduced only to the front wheels, only to the rear wheels and to both front and rear wheels of FWD, RWD and AWD vehicles. Based on the evaluation, the most appropriate wheels on which to use the system are discussed for each type of drive system, together with required vectoring torques. Through these works, the paper shows that the calculation method is also useful for determining the maximum vectoring torque required of the system.

2. Right-and-left torque vectoring system

Fig. 1 shows the operation of the right-and-left torque vectoring system. The system works by controlling the direction and magnitude of torque T_v transmitted between the left and right wheels (this is called torque vectoring), which results in driving force T_v/R acting on one wheel and braking force $-T_v/R$ acting on the other wheel. This then generates longitudinal driving force difference ΔD and, as a result, yaw moment M_g acts on the vehicle. When $T_v = 0$, engine torque T_e is equally divided and distributed to the left and right wheels.

This system is capable, by means of torque vectoring, of controlling the difference in longitudinal driving force between the left and right wheels and yaw moment at any time even when engine torque is fluctuating and/or the vehicle is decelerating. This means that the system can be applied not only to the drive wheels but also to the non-driving wheels.

3. Impact of the system on vehicle dynamics limit

The right-and-left torque vectoring system influences vehicle dynamics in two ways. Firstly, the optimum distribution of driving force between the left and right wheels expands the cornering limit. Secondly, the optimum distribution of cornering force between the front and rear wheels also expands the cornering limit.

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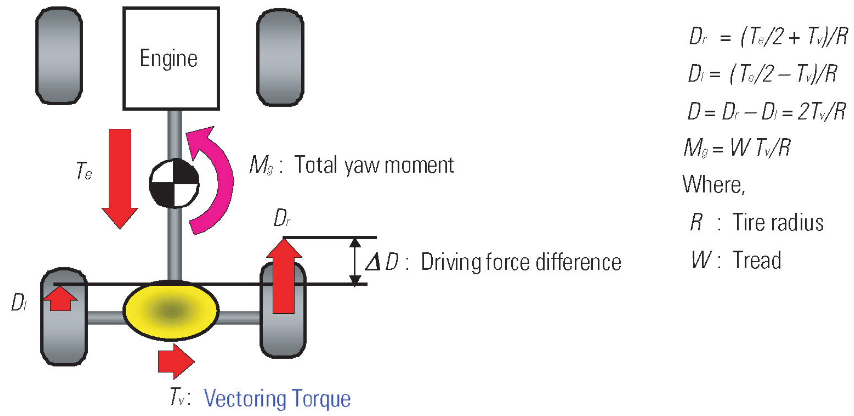


Fig. 1 Definition of right-and-left torque vectoring

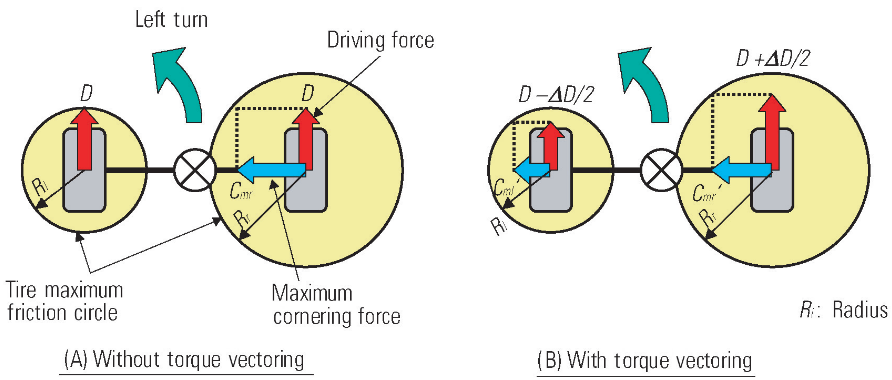


Fig. 2 Effect of torque vectoring #1

Fig. 2 shows the maximum frictional forces of the left and right tires, the driving forces acting on both tires and the maximum cornering force available under these conditions, while the vehicle is turning to the left. In a left turn, due to associated lateral load transfer the frictional force circle of the left tire (R_l) is smaller than that of the right tire (R_r). In the case of (A), which is without left-and-right torque vectoring, the frictional force of the left tire R_l is assumed to be equal to driving force D. The same driving force D that acts on the left tire also acts on the right tire. This driving force D, however, is smaller than the frictional force of the right tire R_r. As a result, only the right wheel is capable of generating the maximum cornering force C_{mr}. In the case of (B), which is with torque vectoring, the left tire, on which driving force $D - \Delta D/2$ acts, is capable of generating the maximum cornering force C_{ml}'. The right tire, on which driving force $D + \Delta D/2$ acts, is also capable of generating the maximum cornering force C_{mr}'. With this, variation ΔC_m in the total maximum cornering force of both tires with right-and-left torque vectoring can be expressed as follows.

$$\begin{aligned}\Delta C_m &= C_{ml}' + C_{mr}' - C_{mr}\\ &= \{R_l^2 - (D - \Delta D/2)^2\}^{1/2} + \{R_r^2 - (D + \Delta D/2)^2\}^{1/2}\\ &\quad - (R_r^2 - D^2)^{1/2}\end{aligned}$$

This equation represents a function where, when ΔD is increased from zero, the maximum value is achieved when:

$$\Delta D = D(R_r - D)/2(D + R_r)$$

This means that right-and-left torque vectoring increases the total maximum cornering force of the left and right tires.

Fig. 3 shows a bicycle model representing a vehicle's steady state cornering. In the case of (A), which is without right-and-left torque vectoring control, the frictional force of the front wheel is assumed to be completely offset by the cornering force C_f (with lateral acceleration: G_Y). The vehicle mass is represented by m, the distance between the center of gravity and the front wheel by L_f, the distance between the center of gravity and the rear wheel by L_r, and the cornering force of the rear wheel by C_r. In the case of (B), which is with lateral torque vectoring control, the cornering force of the front wheel is represented by C_f', the cornering force of the rear wheel by C_r', and yaw moment by M_g. From the equations of steady turning motion for (A) and (B), the following equations can be derived.

$$C_f' = C_f - M_g/(L_f + L_r)$$
$$C_r' = C_r + M_g/(L_f + L_r)$$

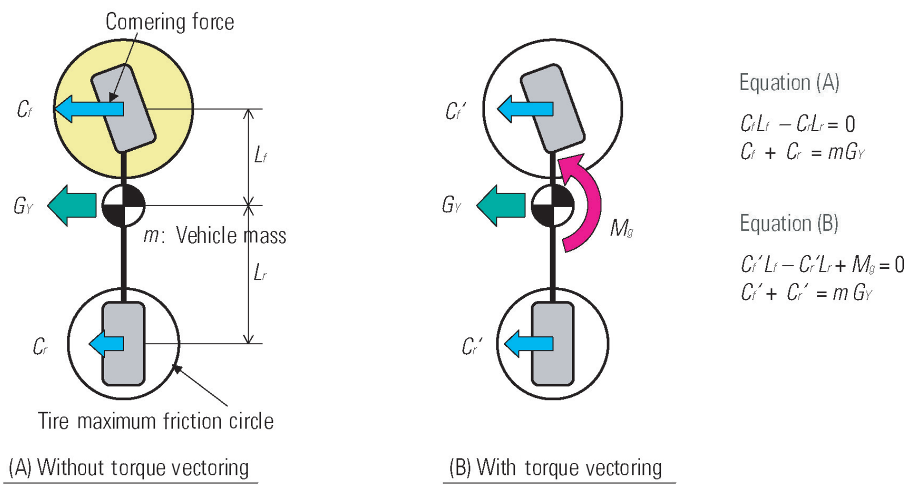


Fig. 3 Effect of torque vectoring #2

This indicates that lateral torque vectoring generates positive (i.e. in the direction of turning) yaw moment on the vehicle, which reduces the distribution of cornering force to the front wheel and thereby expands the cornering limit.

4. Calculation of vehicle dynamics limit

To quantitatively analyze the improvement in vehicle dynamics limit from the application of right-and-left torque vectoring, the equations discussed earlier in this paper were adapted to the dynamic square method for a four-wheel model proposed by Kato et al[6]. Then, using the merged model, a method was developed for calculating front-and-rear driving force distribution, right-and-left torque vectoring on the front wheels and right-and-left torque vectoring on the rear wheels, in order to maximize the vehicle's cornering limit during acceleration and deceleration.

The vehicle model used in the calculation is shown in **Fig. 4**. As the vehicle accelerates (decelerates) with G_X, load transfer occurs along the longitudinal axis of the vehicle. This load transfer ΔW_X, the magnitude of which is proportional to the vehicle's weight, longitudinal acceleration and the height of the center of gravity, and is inversely proportional to the wheelbase, can be expressed as follows.

$$\Delta W_x = m\, G_X\, H_g / L$$

As the vehicle makes a turn with lateral acceleration G_Y, load transfer occurs along the lateral direction of the vehicle. The magnitude of the load transfer is proportional to the vehicle's weight, lateral acceleration and the roll arm length H_s, which is a function of roll stiffness distribution between the front and rear of the vehicle, and is inversely proportional to the treads. With this, the load transfer between the front wheels ΔW_{yf} and that between the rear wheels ΔW_{yr} can be expressed as follows.

$$\Delta W_{yf} = m\, G_Y\{H_s/(1 + K_r/K_f - m\, H_s/K_f) + L_r\, H_f/L\}/W_f$$
$$\Delta W_{yr} = m\, G_Y\{H_s/(1 + K_f/K_r - m\, H_s/K_r) + L_f\, H_r/L\}/W_r$$

With this, the dynamic load distribution between the four wheels can be determined.

By multiplying the dynamic loads for the four wheels by the friction coefficient of the road surface, the maximum frictional force for each wheel as expressed in R_i can be obtained.

Driving force D_i for each wheel can be obtained based on the driving torque from the engine required to achieve G_X, torque distributions T_f and T_r for the front and rear wheels and vectoring torques T_{vf} and T_{vr} between the front wheels and between the rear wheels. The maximum cornering force C_{mi} for each of the four wheels is limited by D_i and R_i, and therefore can be expressed as follows.

$$C_{mi} = (R_i^2 - D_i^2)^{1/2}$$

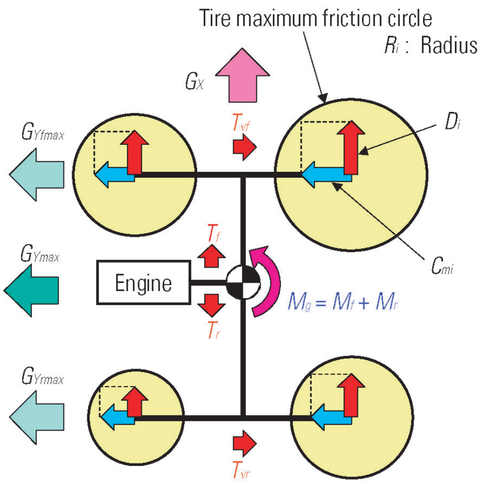
Taking into consideration the impact of yaw moment on the distribution of cornering force between the front and rear wheels as discussed in section 3 of this paper, the maximum lateral acceleration G_{Yfmax} and G_{Yrmax} of the front and rear wheels can be expressed as follows.

$$G_{Yfmax} = (C_{fl} + C_{fr} + M_g/L)/m_f$$
$$G_{Yrmax} = (C_{rl} + C_{rr} - M_g/L)/m_r$$

When these satisfy both of the following inequalities, the relevant turning with assumed lateral acceleration G_Y is valid. If these fail to satisfy either one of the following inequalities, that turning is not valid.

$$G_{Yfmax} \geqq G_Y$$
$$G_{Yrmax} \geqq G_Y$$

By conducting loop calculations using the equations discussed above with G_Y as a parameter, maximum lateral acceleration G_{Ymax} with a given G_X, or the vehicle's cornering limit, can be obtained.



G_X : Longitudinal G
G_{Ymax} : Maximum lateral G
G_{Yfmax}, G_{Yrmax} : Maximum front / rear lateral G
T_f, T_r : Front / rear distribution torque
T_{vf}, T_{vr} : Front / rear vectoring torque
M_f, M_r : Yaw moment generated by front / rear torque vectoring
R_i : Tire maximum friction force of i
D_i : Driving force of i
C_{mi} : Maximum cornering force of i
i = fl, fr, rl, rr : Wheel position
(Front left, Front right, Rear left, Rear right)
m_f, m_r : Front / rear vehicle mass
L : Wheel base
H_g : Height of gravity center
W_f, W_r : Front / rear tread
K_f, K_r : Front / rear vehicle roll stiffness
H_f, H_r : Height of front / rear roll center
H_s : Distance between gravity center and roll axis

Fig. 4 Four-wheel vehicle model

Table 1 Vehicle dimensions

Front vehicle mass (m_f)	(kg)	900
Rear vehicle mass (m_r)	(kg)	600
Wheel base (L)	(m)	2.6
Height of gravity center (H_g)	(m)	0.5
Front tread (W_f)	(m)	1.5
Rear tread (W_r)	(m)	1.5
Front vehicle roll stiffness (K_f)	(N·m/rad)	70,000
Rear vehicle roll stiffness (K_r)	(N·m/rad)	60,000
Height of front roll center (H_f)	(m)	0.05
Height of rear roll center (H_r)	(m)	0.12
Tire radius (R)	(m)	0.32

5. Results of calculations for each type of wheel drive

The cornering limit was calculated for each of FWD, RWD and AWD vehicles corresponding in specifications to those of a C-segment sedan shown in **Table 1** to compare the effect of right-and-left torque vectoring.

5.1 FWD vehicle

Fig. 5 shows the calculated effects of right-and-left torque vectoring on the improvement of cornering limit. **Fig. 6** shows the vectoring torque T_{vf} between the front wheels when torque vectoring was applied only to the front wheels. **Fig. 7** shows the vectoring torque T_{vr} between the rear wheels when torque vectoring was applied only to the rear wheels. **Fig. 8** shows the vectoring torque between the front wheels and that between the rear wheels when torque vectoring was applied to both front and rear wheels.

In the longitudinal acceleration region of 0 – 3 m/s^2, the front wheels reach the maximum lateral acceleration limit before the rear wheels do. This is because, on an FWD vehicle, all the driving force is transmitted to the front wheels. In this region, the lateral acceleration limit for the front wheels can be expanded by applying positive yaw moment to the vehicle by means of right-and-left torque vectoring and thereby reducing the share of the cornering force on the front wheels. The vehicle's cornering limit can be expanded no matter which combination of wheels, front or rear, torque vectoring is applied to. In either case, the required maximum vectoring torque is approximately 500 N·m (**Fig. 6** and **Fig. 7**). However, the extent of improvement is greater when torque vectoring is applied to the front wheels than to the rear wheels. This is because, with the front wheels, it is also possible to optimize the distribution of driving force between them. In fact, the cornering limit with torque vectoring applied to the front wheels is almost equal to that applied to both the front and rear wheels.

In the longitudinal acceleration region of 3 m/s^2 and above, due to lateral load transfer during a turn, the frictional force of the inside front tire is reduced so much as to be offset with only the driving force, and this determines the vehicle's cornering limit. In this case, applying right-and-left torque vectoring control to the rear wheels does not have any effect in reducing the driving force distributed to the inside front tire, and thus has no effect in expanding the cornering limit. On the other hand, applying the control to the front wheels has a significant effect on improving the vehicle's cornering limit. Even greater improvement can be achieved by applying the control to both the front and rear wheels. However, the required maximum vectoring torque between the rear wheels in that case is almost 800 N·m (**Fig. 8**). Thus, this option is not efficient, especially in view of the complexity of the associated system.

In the longitudinal deceleration region of 0 to –4 m/s^2, longitudinal load transfer causes the rear wheels to reach the maximum lateral acceleration limit before the front wheels do. In this region, the lateral acceleration limit for the rear wheels can be expanded by applying negative yaw moment to the vehicle by means of right-and-left torque vectoring. If torque vectoring is applied to the rear wheels, however, the frictional force of the rear wheels is offset with the braking force to generate yaw moment. Therefore, torque vectoring needs to be limited and only a slight improvement in cornering limit is possible. On the other hand, applying torque vectoring to the front wheels not only optimizes the distribution of braking force between the front wheels to improve the front wheels' lateral acceleration limit, but also improves the rear wheels' lateral acceleration limit with negative yaw moment. With this, compared with the acceleration region, the cornering limit can be improved with smaller vectoring torque.

In the longitudinal deceleration region of –4 m/s^2 and beyond, the frictional force of the inside front tire is offset with only the braking force, and this determines the vehicle's cornering limit. Due to this, applying right-and-left torque vectoring to the rear wheels is not effective at all in improving the vehicle's cornering limit. Applying torque vectoring control to the front wheels optimizes the distribution of braking force, thus improving the front wheels' lateral acceleration limit and the vehicle's maximum lateral acceleration limit. If the control is applied to the front and rear wheels, the negative yaw moment generated by the front wheels is offset by the positive yaw moment generated by the rear wheels. This expands the front wheels' lateral acceleration limit and slightly improves the vehicle's cornering limit.

To summarize, on FWD vehicles, application of right-and-left torque vectoring control to the front wheels effectively expands the cornering limit. The required maximum vectoring torque is approximately 500 N·m.

5.2 RWD vehicle

Fig. 9 to **Fig. 12** show the results of calculations for RWD vehicles. In the longitudinal acceleration region of 0 to 0.5 m/s^2, longitudinal load shift causes the front wheels to reach the maximum lateral acceleration limit before the rear wheels do. Because of this, applying right-and-left torque vectoring to the rear wheels to generate yaw moment improves the vehicle's cornering limit, but only slightly. Then, in the longitudinal acceleration region of 0.5 m/s^2 and above, the frictional force of the inside rear tire is offset with only the driving force, and this determines the vehicle's cornering limit. Application of torque vectoring control to the front wheels is not effective at all while its application to the rear wheels is fairly effective. The required maximum vectoring torque in this case is approximately 400 N·m (**Fig. 11**). With the control applied to the front and rear

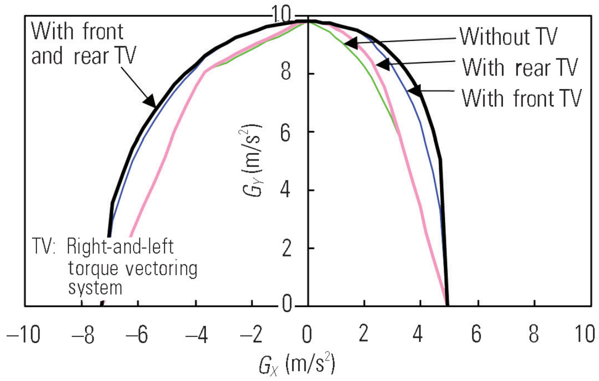


Fig. 5 Vehicle dynamics limit with FWD

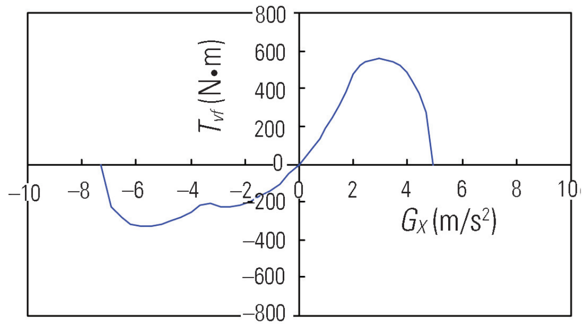


Fig. 6 Front wheel right-and-left vectoring torque

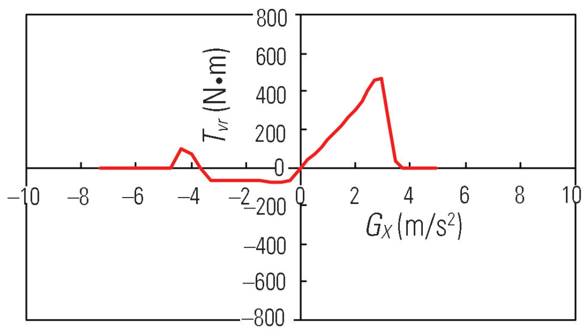


Fig. 7 Rear wheel right-and-left vectoring torque

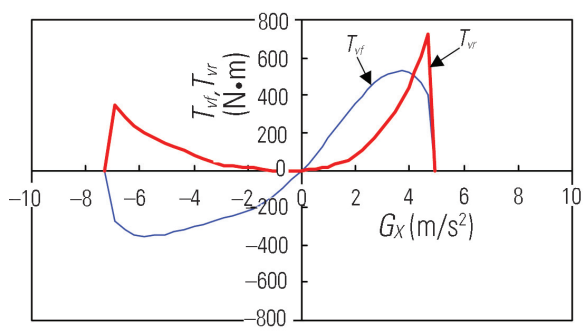


Fig. 8 Front and rear wheel right-and-left vectoring torque

wheels, the positive yaw moment generated by the rear wheels, which lowers the lateral acceleration limit for the rear wheels, is balanced by the negative yaw moment generated by the front wheels, improving the vehicle's cornering limit. The required maximum vectoring torque between the front wheels in this case, however, is as much as around 800 N·m (**Fig. 12**).

In the longitudinal deceleration region of 0 to –0.5 m/s^2, the rear wheels reach the lateral acceleration limit before the front wheels do and the vehicle's cornering limit can be expanded equally by applying torque vectoring control to either the front or rear wheels. In the longitudinal deceleration region of –0.5 m/s^2 and beyond, the frictional force of the inside rear wheel is offset with only the braking force, and this determines the vehicle's cornering limit. In this case, applying right-and-left torque vectoring control to the front wheels is not effective at all while its application to the rear wheels is effective. Applying the control to the front and rear wheels is more effective, however, this requires a substantial amount of vectoring torque as with the case of accelerating while cornering.

To summarize, on RWD vehicles, application of right-and-left torque vectoring to the rear wheels is effective in raising the vehicle's cornering limit. The required maximum vectoring torque is approximately 400 N·m.

5.3 AWD vehicle

Fig. 13 to **Fig. 16** show the results of calculations for AWD vehicles. In each case, the calculations are based on the calculated optimum driving force distribution between the front and rear wheels that achieved the highest cornering limit.

In the longitudinal acceleration region, the front and rear wheels always reach the lateral acceleration limit at the same time due to optimized driving force distribution between the front and rear wheels. As a result, a smooth curve of cornering limit has been plotted. In addition, the cornering limit is expanded across the entire acceleration range no matter which pair of wheels, front or rear, right-and-left torque vectoring control is applied to. The calculations in our study indicate that the control is slightly more effective when it is applied to the rear wheels than to the front wheels. The required maximum vectoring torque is approximately 500 N·m when the control is applied to the front wheels (**Fig. 14**), and approximately 400 N·m when it is applied to the rear wheels (**Fig. 15**). Therefore, the cornering limit can be expanded more efficiently by applying the control to the rear wheels. Application of the control to both the front and rear wheels is more effective on AWD vehicles than on FWD and RWD vehicles.

In the longitudinal deceleration region of 0 to –5 m/s^2, without right-and-left torque vectoring, the rear wheels reach the lateral acceleration limit before the front wheels do. In the deceleration region of –5 m/s^2 and beyond, the front and rear wheels reach the lateral acceleration limit at the same time as in the case of accelerating while cornering. Therefore, as in acceleration, the cornering limit can be expanded throughout

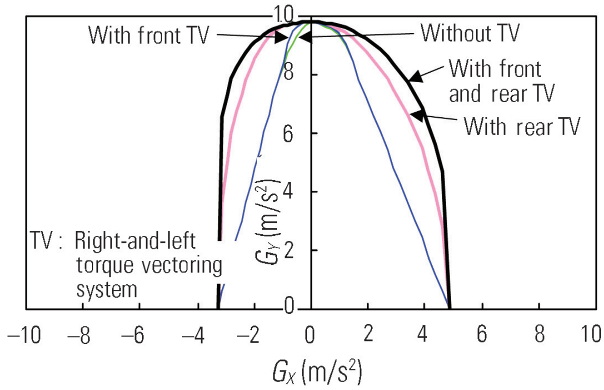


Fig. 9 **Vehicle dynamics limit with RWD**

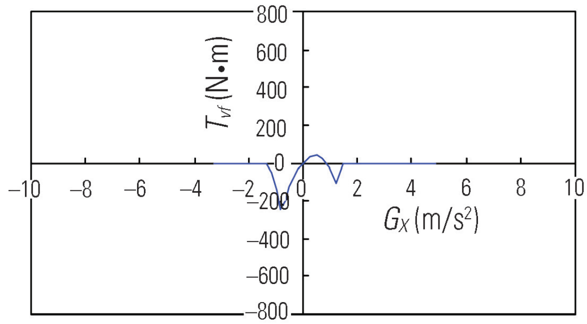


Fig. 10 **Front wheel right-and-left vectoring torque**

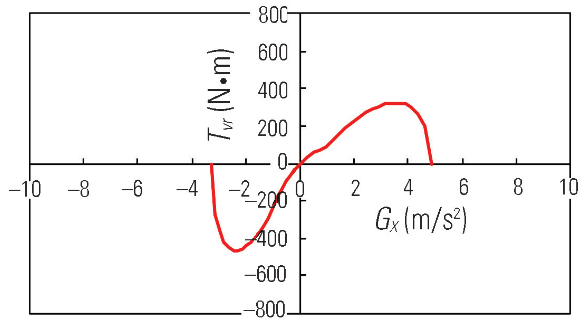


Fig. 11 **Rear wheel right-and-left vectoring torque**

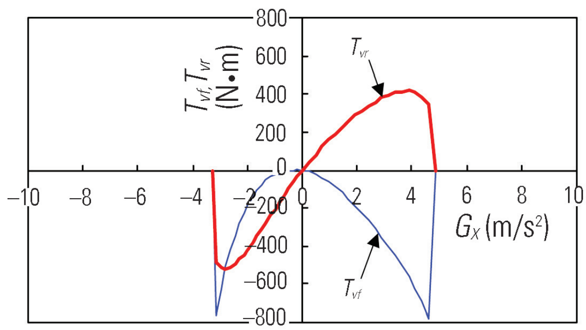


Fig. 12 **Front and rear wheel right-and-left vectoring torque**

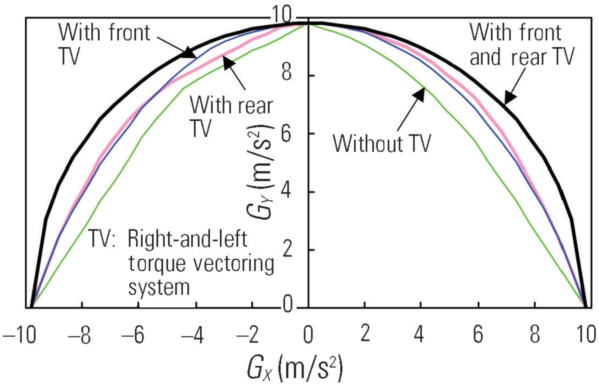


Fig. 13 Vehicle dynamics limit with AWD

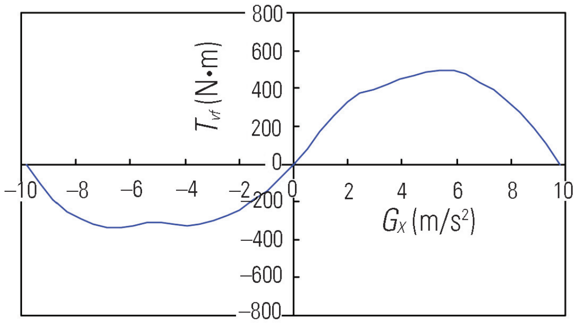


Fig. 14 Front wheel right-and-left vectoring torque

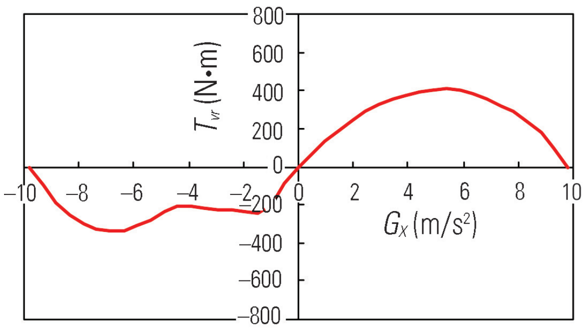


Fig. 15 Rear wheel right-and-left vectoring torque

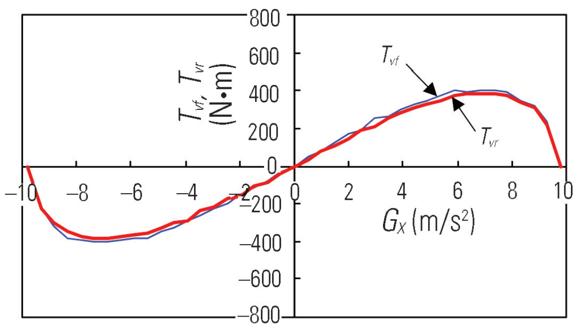


Fig. 16 Front and rear wheel right-and-left vectoring torque

the entire deceleration range by applying right-and-left vectoring control to either the front wheels or the rear wheels. The improvement is substantial when the control is applied to both the front and rear wheels.

To summarize, on AWD vehicles, it is most effective to apply right-and-left torque vectoring control to both the front and rear wheels. If the control is to be applied to either the front or rear wheels in order to avoid system complexity, it is preferable to apply it to the rear wheels, since this results in a greater improvement in cornering limit with a smaller vectoring torque.

6. Summary

This paper discussed equations representing the functions of the right-and-left torque vectoring system, its applicability to non-driving wheels and its effect on the vehicle's cornering limit. The system was adapted to the dynamic square analysis method to calculate its effectiveness in expanding the vehicle's cornering limit for each drive type, and the following results were obtained.

The system is most effective when applied to the front wheels on FWD vehicles and to the rear wheels on RWD and AWD vehicles.

The calculation method used in this study is useful in determining the required maximum vectoring torque for a right-and-left torque vectoring system.

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