

**SAE TECHNICAL
PAPER SERIES**

2007-01-3645

Effect of the Right-and-left Torque Vectoring System in Various Types of Drivetrain

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**14th Asia Pacific Automotive
Engineering Conference
Hollywood, California, USA
August 5-8, 2007**

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-0790 Web: www.sae.org

JTEKT Corporation Ex. 1009, pg.1
JTEKT v. GKN
IPR2016-00046

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ISSN 0148-7191

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Printed in USA

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ABSTRACT

This paper describes the calculative verification of the effect of the right-and-left torque vectoring system in various types of drivetrain, namely, the front wheels only, the rear wheels only, and both front and rear wheels in FWD, RWD, and AWD vehicles. The effect is evaluated by calculating the vehicle dynamics limit; maximum acceleration and cornering ability. The right-and-left vectoring torque, which is needed for expanding the vehicle dynamics limit, is also calculated. And finally, the paper evaluates the suitable wheels for which the system should be applied in each drivetrain. The application to the front wheels is more effective for FWD vehicles. On the other hand, the application to the rear wheels is more effective for RWD and AWD vehicles.

INTRODUCTION

Various technologies for vehicle dynamic control have been developed since the 1980s. The yaw control is effective in order to realize the active safety philosophy that makes occurrence probability of an accident small, and the yaw control technology by using brake systems has progressed and become common. As a next step, the direct yaw control by using the right-and-left torque vectoring system is in the limelight. This system can directly control the yaw moment act on a vehicle by vectoring torque between wheels on either side with minimum energy loss. Therefore, the strong point of this system is to be able to improve vehicle driving stability from the usual driving condition to the high marginal driving condition seamlessly ⁽¹⁾.

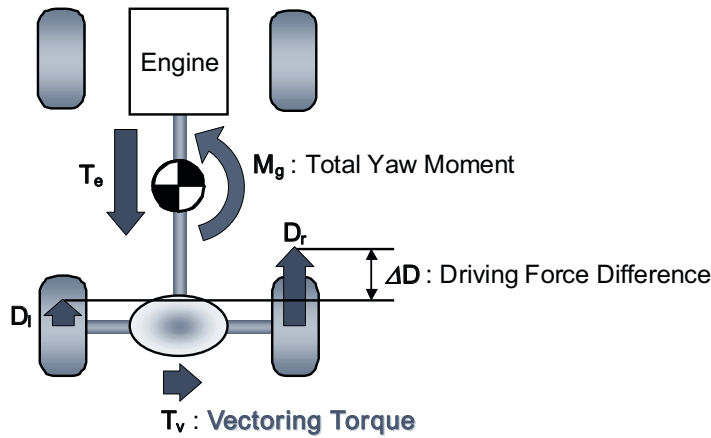
The authors applied the right-and-left torque vectoring system to the rear wheels of AWD (All Wheel Drive) vehicles ⁽²⁾ in 1996. This is the first application of the vectoring system to production vehicles in the world, and is still the only one today as well. Other production applications of this system had existed only for the front wheels of a FWD (Front Wheel Drive) vehicle ⁽³⁾ in the past. The effect of this system is discussed in the latest

research report ⁽⁴⁾⁽⁵⁾ in case of applying to the rear wheels of an AWD vehicle or a RWD (Rear Wheel Drive) vehicle, however, there is no report discussing the effect in the application to the front wheels of AWD vehicles or the rear wheels of FWD vehicles.

This paper describes the calculative verification of the effect of the right-and-left torque vectoring system in various types of drivetrain, namely, the front wheels only, the rear wheels only, and both front and rear wheels in FWD, RWD, and AWD vehicles. At first, the right-and-left torque vectoring system is defined, and the applicability of this system to non driving wheels such as the rear wheels of FWD vehicle is described. The second, the principle about the influence on a vehicle dynamics performance by this system is shown. The numerical analysis evaluation method of the vehicles dynamics limit with consideration of this system, and the calculation results of the effect of this system in various types of drivetrain are shown. The maximum vectoring torque, which is needed for expanding the vehicle dynamics limit, is also described. And finally, the paper evaluates the suitable wheels for which the system should be applied in each drivetrain.

DEFINITION OF RIGHT-AND-LEFT TORQUE VECTORING

The authors define a right-and-left torque vectoring system as a device that can control both the torque flow amount and its direction between right and left wheels (these are defined as vectoring torque), so that it can make one side of the driving forces small, and another side of the driving forces large. Consequently, the system generates longitudinal force difference between right and left wheels, and can control yaw moment that acts on vehicles. This concept is shown in Fig. 1. Even if the engine torque changes or breaking force is applied, this system can control the same longitudinal force difference between right and left wheels, and the same yaw moment, which works on vehicles at any time using the same vectoring torque. Moreover, the feature, that vectoring torque can be controlled without influence of



$$D_r = (T_e/2 + T_v)/R$$

$$D_l = (T_e/2 - T_v)/R$$

$$\Delta D = D_r - D_l = 2T_v/R$$

$$M_g = W T_v/R$$

Where,

R : Tire Radius

W : Tread

Fig.1 Definition of Right-and-left Torque Vectoring

the driving torque supplied by the engine, mean that this system can be applied also to the non-driving wheels instead of driving wheels of a vehicle.

PRINCIPLE OF RIGHT-AND-LEFT TORQUE VECTORING EFFECT FOR VEHICLE DYNAMICS

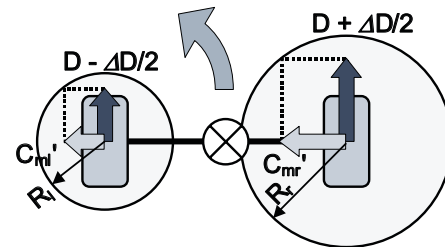
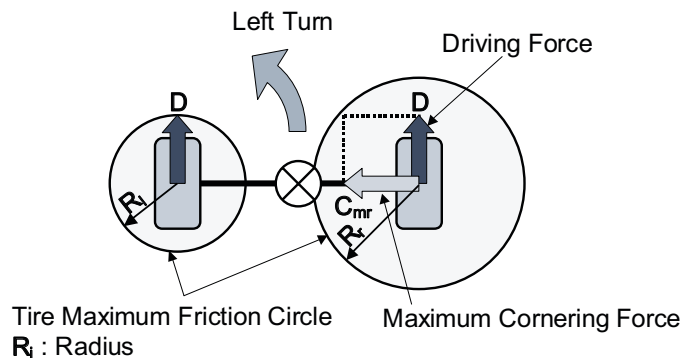
A right-and-left torque vectoring system has two effects on vehicle dynamics. The first is that the total maximum cornering force of the right and left wheels increases. This occurs because the system optimizes the driving force assignment between the right and left wheels. The second effect on vehicle dynamics is that the cornering force assignment between the front and the rear wheels is optimized. This occurs because the system generates a yaw moment. In both cases, the vehicle dynamics limit improves.

Figure 2 shows the relation between the tire maximum friction force, the driving force, and the maximum cornering force of the right and left wheels during cornering. While the vehicle is cornering left, a lateral acceleration causes the left tire maximum friction force R_l (that is shown as a radius of the tire maximum friction

circle) to decrease and the right tire maximum friction force R_r to increase. Therefore R_l is smaller than R_r . The left tire maximum friction force same R_l and the left driving force D assume an equal state in case of a vehicle without torque vectoring shown in Fig. 2 (A). In this state, the right wheel can only generate the maximum cornering force C_{mr} in (A), because the right tire maximum friction force R_r is bigger than the right driving force D . On the other hand, in case of a vehicle with torque vectoring in Fig. 2 (B), the left driving force is $D - \Delta D/2$ and the right driving force is $D + \Delta D/2$, so that the left wheel can generate the maximum cornering force C_{ml}' and the right wheel can generate the maximum cornering force C_{mr}' . Denoting the right and left wheels total maximum cornering force difference between a vehicle with torque vectoring and a without torque vectoring by ΔC_m , it is expressed by the following formula,

$$\Delta C_m = C_{ml}' + C_{mr}' - C_{mr}$$

$$= \{R_l^2 - (D - \Delta D/2)^2\}^{1/2} + \{R_r^2 - (D + \Delta D/2)^2\}^{1/2} - (R_r^2 - D^2)^{1/2}$$



(A) Without Torque Vectoring

(B) With Torque Vectoring

Fig.2 Effect of Torque Vectoring #1

In this formula, when ΔD is increasing from zero, ΔC_m becomes maximum value at

$$\Delta D = D(R_f - D) / 2(D + R_f).$$

Thus, it is shown that a torque vectoring increases the total maximum cornering force.

Figure 3 shows bicycle models of vehicles during steady state cornering. Assuming the cornering state (lateral acceleration: G_Y) where the front cornering force C_f consumes the front tire maximum friction force R_f altogether in case of a vehicle without right-and-left torque vectoring shown in Fig. 3 (A), the vehicle's cornering limit (that is maximum lateral acceleration) of (A) is G_Y . Where m is the vehicle mass, L_f is the distance between front wheels and a gravity center, L_r is the distance between rear wheels and the gravity center, and C_r is the rear cornering force. On the other hand, denoting the front cornering force by C'_f , the rear cornering force by C'_r , and the yaw moment by torque vectoring by M_g in case of a vehicle with torque vectoring in Fig. 3 (B), the following formulas are obtained from the vehicle dynamics equations of (A) and (B) vehicles in Fig.3.

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

$$C'_r = C_r + M_g / (L_f + L_r)$$

From this expression, it may be concluded that when the positive (the same as cornering direction) yaw moment is added on vehicles by torque vectoring, the needed front cornering force becomes small, and the vehicle's cornering limit improves.

ANALYSIS METHOD OF VEHICLE DYNAMICS LIMIT

In order to numerically analyze the improvement of

vehicle's cornering limit made by the right-and-left torque vectoring, the authors used the torque vectoring effect formula shown above. This formula was installed into the four-wheel model of dynamic square method⁽⁶⁾ that Kato et al. proposed. The authors used this calculation method to obtain the optimal values for the front-and-rear distribution torque, the right-and-left vectoring torque between front wheels, and the right-and-left vectoring torque between rear wheels. The calculation was used to determine the vehicle's cornering limit during acceleration/deceleration.

The calculation vehicle model is shown in Fig. 4. Assuming that a vehicle is accelerating with longitudinal acceleration G_X , a load transfer (weight shift) occurs between front and rear wheels. The load transfer between front and rear wheels is denoted as ΔW_x . Since ΔW_x is proportional to vehicle mass, longitudinal acceleration, height of gravity center, and inversely proportional to wheelbase, we can find the following equation,

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

Assuming a vehicle is cornering at lateral acceleration G_Y , a load transfer occurs between right and left wheels. Since the load transfer between right and left wheels is proportional to vehicle mass, lateral acceleration, roll arm length (obtained from the roll stiffness balance between front and rear wheels), and inversely proportional to tread, the two equations below are generated. Denoting the load transfer between right and left front wheels by ΔW_{yf} , and the load transfer between right and left rear wheels by ΔW_{yr} ,

$$\Delta W_{yf} = m G_Y \{ (H_g / (1 + K_f / K_r - m H_g / K_f) + L_r H_f / L) / W_f$$

$$\Delta W_{yr} = m G_Y \{ (H_g / (1 + K_f / K_r - m H_g / K_r) + L_f H_r / L) / W_r$$

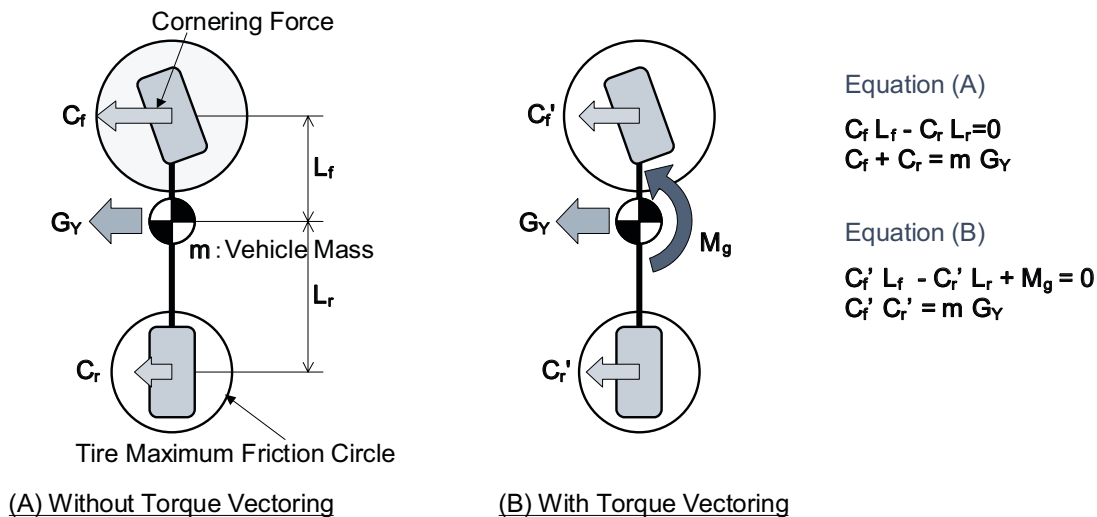
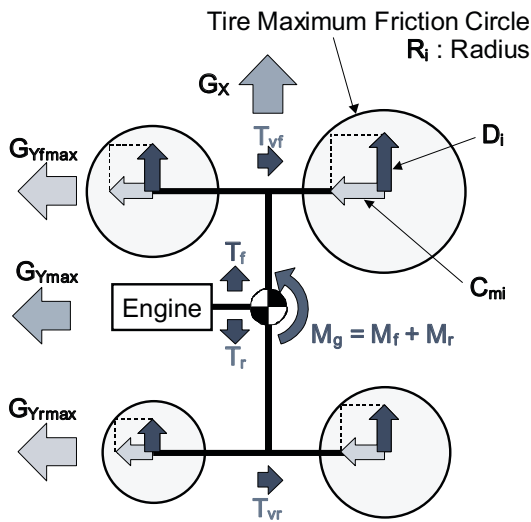


Fig.3 Effect of Torque Vectoring #2



G_x : Longitudinal G
 $G_{y_{max}}$: Maximum Lateral G
 $G_{yf_{max}}, G_{yr_{max}}$: 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

Thus, we can obtain the load of each four wheel.

When the load is multiplied by the road surface friction coefficient, the maximum tire friction force of each four wheel, which is expressed as the friction circle radius R_i , can be calculated.

Next, the driving force of each wheel D_i is obtained from the engine torque that is required for G_x , front and rear distribution torque, front wheel's right-and-left vectoring torque, and rear wheel's right-and-left vectoring torque. D_i and R_i limit a cornering force as shown in Fig. 4. Therefore, the maximum cornering force of each four wheel C_{mi} is,

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

When the yaw moment influence described in previous section (namely, a yaw moment influence on the cornering force which each of front and rear wheels should share) is taken into consideration, the maximum lateral acceleration, $G_{yf_{max}}$ and $G_{yr_{max}}$, can be generated at each of front and rear wheels, shown below,

$$G_{yf_{max}} = (C_{fl} + C_{fr} + M_g / L) / m_f$$

$$G_{yr_{max}} = (C_{rl} + C_{rr} - M_g / L) / m_r$$

In the case that the both of these values exceed the assumed lateral acceleration G_y , where the inequalities below are both satisfied, the vehicle can corner at G_y . On the contrary, in the case that these values don't satisfy either of the following inequalities, the vehicle cannot corner at G_y .

$$G_{yf_{max}} \geq G_y$$

$$G_{yr_{max}} \geq G_y$$

Satisfying the above inequalities, the lateral acceleration G_y is increased, then its maximum, which limits the cornering, is determined.

ANALYSIS RESULTS IN VARIOUS TYPES OF DRIVETRAIN

By using the analysis method described in previous section, authors calculated the effect of the right-and-left torque vectoring system in various type of drivetrain, namely, FWD vehicles, RWD vehicles, and AWD vehicles with the dimensions shown in Table 1. These are the dimensions of a typical C-segment sedan. For the AWD vehicles, their optimal front-and-rear torque distribution was calculated.

FWD VEHICLES

Figure 5 shows the calculation results of the vehicle dynamics limit of the FWD vehicle and the results of the

Table 1 Vehicle Dimensions

Front Vehicle Mass (m_f)	900 kg
Rear Vehicle Mass (m_r)	600 kg
Wheel Base (L)	2.6 m
Height of Gravity Center (H_g)	0.5 m
Front Tread (W_f)	1.5 m
Rear Tread (W_r)	1.5 m
Front Vehicle Roll Stiffness (K_f)	70000 Nm/rad
Rear Vehicle Roll Stiffness (K_r)	60000 Nm/rad
Height of Front Roll Center (H_f)	0.05 m
Height of Rear Roll Center (H_r)	0.12 m
Tire Radius (R)	0.32 m

vehicle dynamics improvement effect by right-and-left torque vectoring system. At that time, Fig. 6-8 are generated. The front wheel right-and-left vectoring torque of the vehicle with the right-and-left torque vectoring for the front wheels only is shown in Fig. 6, the rear wheel right-and-left vectoring of the vehicle with right-and-left torque vectoring for the rear wheels only is shown in Fig. 7, and the front and rear wheels right-and-left vectoring torque of the vehicle with right-and-left torque vectoring for both front and rear wheels are shown in Fig. 8.

In the FWD vehicles with the gravity center near the front wheels, the maximum friction force of the front wheels is bigger than that of the rear wheels. However, since all driving force is transferred to the front wheels, in the longitudinal acceleration domain of 0 to 3 m/s², the maximum front lateral acceleration reaches the limit faster than the rear wheels. Addition of positive yaw moment by a right-and-left torque vectoring increases the maximum front lateral acceleration in this domain. Therefore, as we can see in Fig. 5, the right-and-left torque vectoring for both front and rear wheels can improve the vehicle's cornering limit. In both cases, the required maximum vectoring torque is about 500 Nm shown in Fig. 6 and 7.

In the domain of longitudinal acceleration larger than 3 m/s², the vehicle's cornering limit is restricted because the friction force of a cornering inner side wheels becomes small by the load transfer between the right and left wheels and the front inner wheel reaches the friction force limit by the driving force only. In this case, right-and-left torque vectoring applied to the rear wheels does not have a significant effect on the vehicle's cornering limit because this configuration does not have the effect of decreasing the driving force of the front wheel of a cornering inner side. The effect of right-and-left torque vectoring applied to the front wheel is large. Although application to both front and rear wheels is also further effective, the maximum vectoring torque of a required rear wheels amounts to about 800 Nm in this case shown in Fig. 8. Therefore, considering the complexity of a system configuration, the application to both of front and rear wheels is not an efficient system.

Next, in the longitudinal acceleration domain of 0 to -4 m/s², the maximum rear lateral acceleration reaches the limit faster than the front wheels. Addition of negative yaw moment by a right-and-left torque vectoring can increase the maximum rear lateral acceleration in this domain. However, when torque vectoring is applied to the rear wheels, the friction force of the rear wheels will be consumed as driving/braking force in order to generate yaw moment. Therefore, only a small amount of torque can be vectored, giving only minor improvements of the vehicle's cornering limit. On the other hand, when a torque vectoring is applied to front wheels, the maximum front lateral acceleration improves according to the rationalization effect of the braking force assignment between right and left front wheels, and the maximum rear lateral acceleration is improved by the

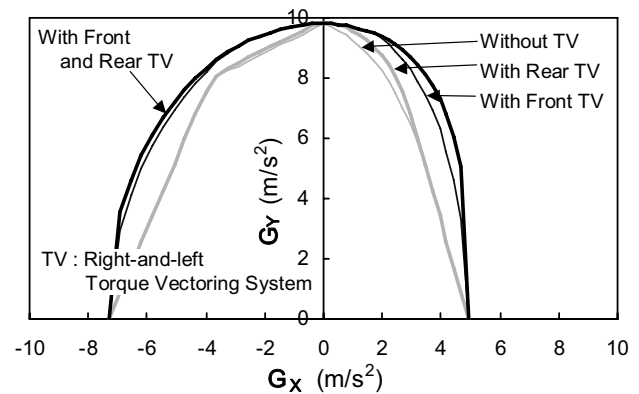


Fig.5 Vehicle Dynamics Limit of FWD

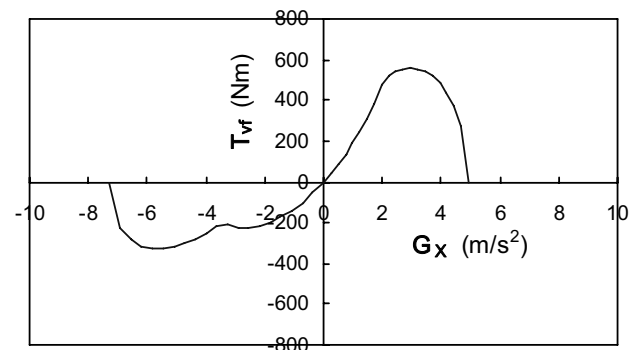


Fig.6 Front Wheel Right-and-left Vectoring Torque

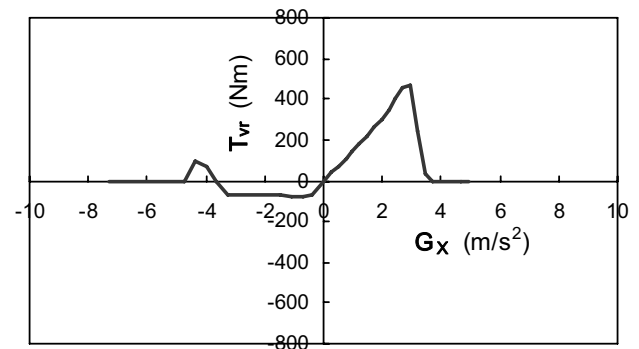


Fig.7 Rear Wheel Right-and-left Vectoring Torque

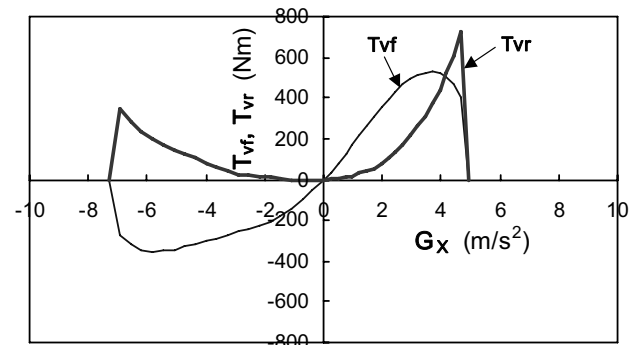


Fig.8 Front and Rear Wheel Right-and-left Vectoring Torque

negative yaw moment. Therefore, when compared with a domain positive in acceleration, there is a big improvement of vehicle's cornering limit with small vectoring torque.

In the domain lower than -4 m/s^2 where longitudinal deceleration is still bigger, the front wheel of a cornering inner side reaches the friction force limit by the braking force only, and the vehicle's cornering limit is restricted. Therefore, the torque vectoring application to the rear wheels is completely ineffective. When the torque vectoring is applied to front wheels, the maximum front lateral acceleration is improved by rationalization of a right and left braking force assignment, and the maximum lateral acceleration of the vehicles also improves. Moreover, when the torque vectoring is applied to the rear wheels in addition to the front wheels, according to the reason positive yaw moment generated by the rear wheels negates negative yaw moment generated by the front wheels, the maximum front lateral acceleration can be improved further. Although the improvement is small, there is the combined use effect of both front and rear wheels' torque vectoring in this domain.

Form the above result, in the case of a FWD vehicle, the torque vectoring application to the front wheels is the most effective, and the maximum vectoring torque required for this system is about 500 Nm.

RWD VEHICLES

The calculation results about the RWD vehicle are shown in Figs. 9-12. In the longitudinal acceleration domain of 0 to 0.5 m/s^2 , the maximum front lateral acceleration reaches the limit faster than the rear wheels. Therefore, even when the torque vectoring is applied to the front wheels, the vehicle's cornering limit improves slightly according to the effect of positive yaw moment. But, in the domain higher than 0.5 m/s^2 , since the rear wheel of a cornering inner side reaches the friction force limit only in the driving force and the vehicle's cornering limit is restricted, the torque vectoring application to the front wheels is completely ineffective. However, the effect of torque vectoring application to the rear wheels is large. At that time, the required maximum vectoring torque at the rear wheels is about 400 Nm shown in Fig. 11. Furthermore, when the torque vectoring is applied also to the front wheels in addition to the rear wheels, the phenomenon in which the maximum rear lateral acceleration decreases by positive yaw moment generated by the rear wheels is compensated by negative yaw moment generated by the front wheels, and the cornering force assignment between front and rear wheel is improved. Therefore, the vehicle's cornering limit improves further. However, at that time, the maximum vectoring torque of the front wheels required amounts to about 800 Nm shown in Fig. 12.

Next, in the longitudinal acceleration domain of 0 to -0.5 m/s^2 , the maximum rear lateral acceleration reaches the limit faster than the front wheels. Therefore, both front

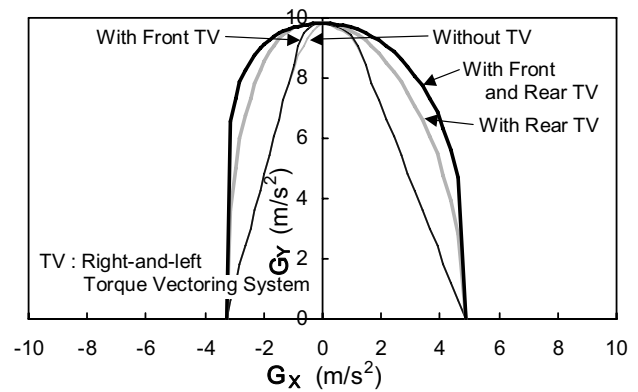


Fig.9 Vehicle Dynamics Limit of RWD

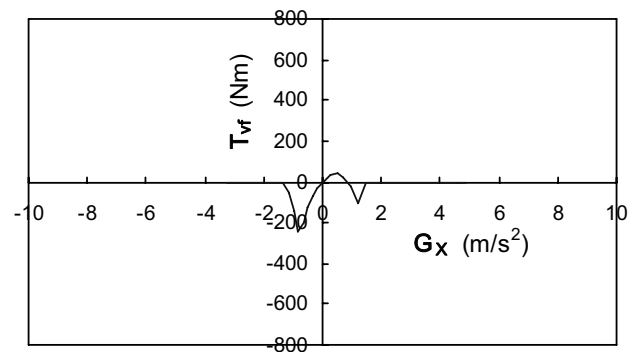


Fig.10 Front Wheel Right-and-left Vectoring Torque

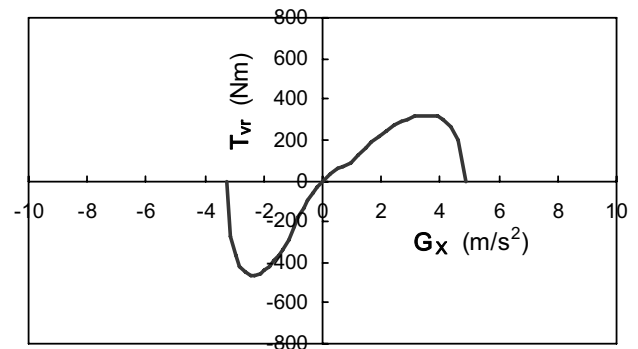


Fig.11 Rear Wheel Right-and-left Vectoring Torque

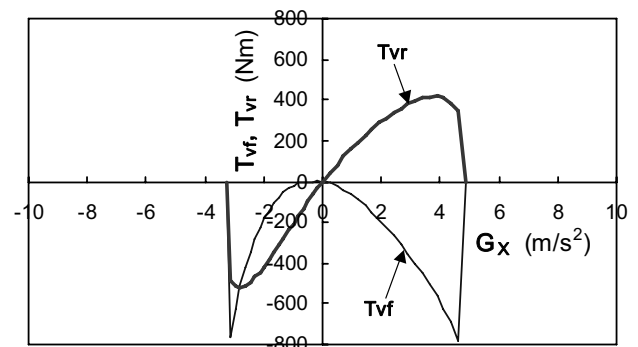


Fig.12 Front and Rear Wheel Right-and-left Vectoring Torque

and rear wheels' right-and-left torque vectoring improves the vehicle's cornering limit. However, in the domain lower than -0.5 m/s^2 , the rear wheel of a cornering inner side reaches the friction force limit by the braking force only, and the vehicle's cornering limit is restricted. Therefore, the torque vectoring application to the front wheels is completely ineffective. Only the application to the rear wheels is effective. When the torque vectoring is applied to both front and rear wheels, the vehicle's cornering limit improves further, but the maximum vectoring torque required is also increases.

Form the above result, in the case of a RWD vehicle, the torque vectoring application to the rear wheels is the most effective, and the maximum vectoring torque required for this system is about 400 Nm.

AWD VEHICLES

The calculation results about the AWD vehicle are shown in Figs. 13-16. Regarding the front and rear torque distribution of AWD vehicle, the torque distribution that makes the vehicle's cornering limit the highest in each application is obtained at same time. The front and rear torque distribution is shown in Fig. 17.

In the acceleration domain positive in the case of an AWD vehicle, since both front and rear maximum lateral acceleration always reaches the friction force limit simultaneously due to optimization of torque distribution between front and rear wheels, the vehicle's cornering limit line draws a smooth curve shown in Fig. 13. Also both front and rear wheels' right-and-left torque vectoring has the similar improvement effect on the vehicle's cornering limit in all domain, but the application to the rear wheels is slightly more effective than the application to the front wheels with assumed vehicle dimension. Moreover, in the case of the front wheel application, the required maximum vectoring torque is about 500 Nm shown in Fig. 14. In the case of the rear wheel application, it is about 400 Nm shown in Fig. 15. Therefore, application of torque vectoring to the rear wheels can improve the vehicle's cornering limit more effectively. Additionally, in the case of an AWD vehicle compared with a FWD vehicle or a RWD vehicle, the improvement by application to both wheels is large. At that time, the optimal driving force distribution between front and rear draws the curve proportional to the dynamic front and rear load assignment shown in Fig. 17.

Next, in the longitudinal acceleration domain of 0 to -5 m/s^2 negative i.e. deceleration, the maximum rear lateral acceleration reaches the limit faster than the front wheels in case of the vehicle without torque vectoring. And in the domain lower than -5 m/s^2 , both of front and rear maximum lateral acceleration always reaches limit simultaneously because of the same reason as positive acceleration domain. Therefore, both of front and rear wheels' right-and-left torque vectoring has the improvement effect of a vehicle's cornering limit in all domain, and the improvement effect by application to both wheels is also large.

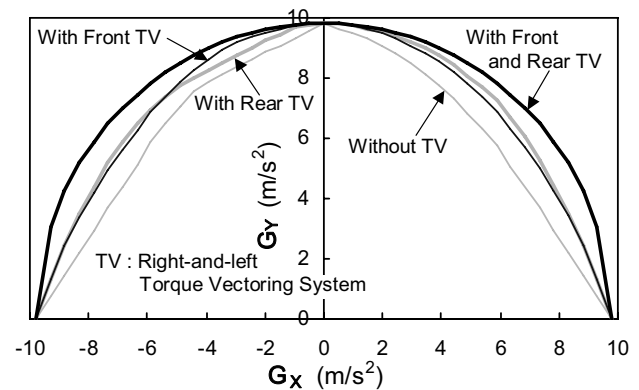


Fig.13 Vehicle Dynamics Limit of AWD

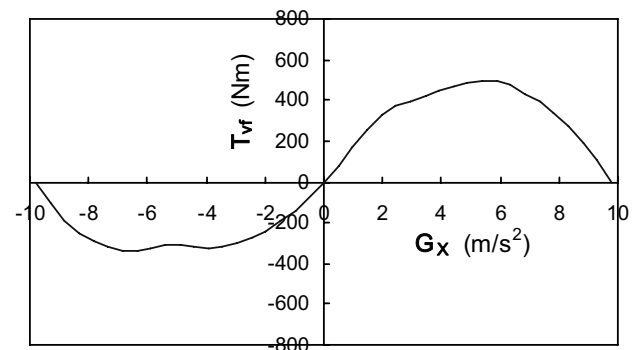


Fig.14 Front Wheel Right-and-left Vectoring Torque

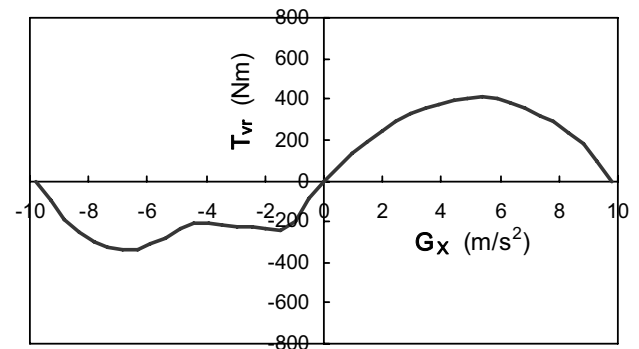


Fig.15 Rear Wheel Right-and-left Vectoring Torque

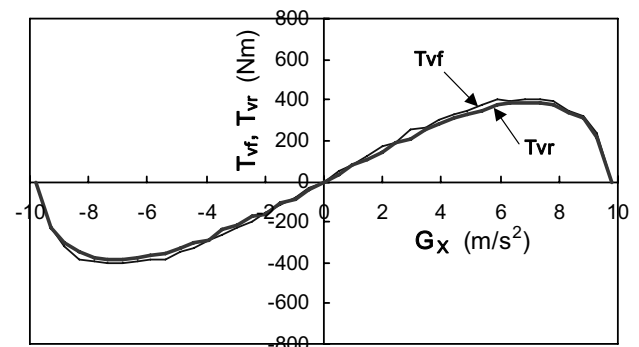


Fig.16 Front and Rear Wheel Right-and-left Vectoring Torque

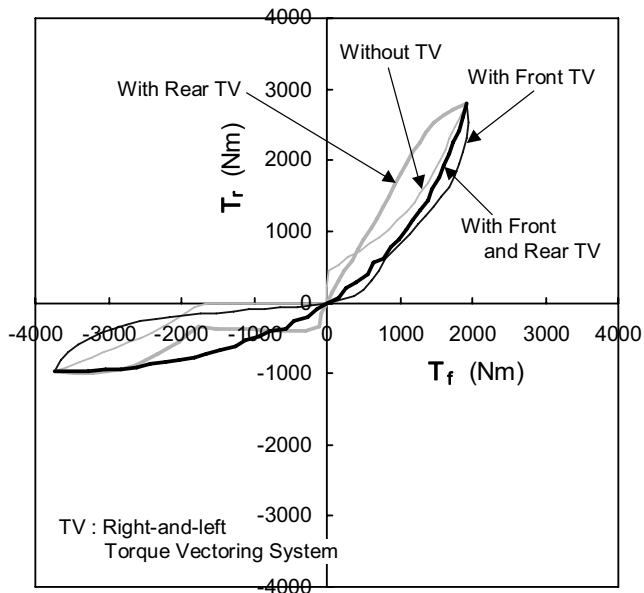


Fig.17 Front and Rear Torque Distribution

From the above result, in the case of an AWD vehicle, the torque vectoring application to the both of front and rear wheels is effective. However, in order to avoid complication of a system, when applying the torque vectoring only to one of front or rear wheels, since the same improvement can be realized with smaller maximum vectoring torque, application to the rear wheels is better.

CONCLUSION

The applicability of right-and-left torque vectoring system to non driving wheels was described with the equation of a longitudinal force and yaw moment, which works on vehicles with the described system.

The principle of the influence of this system on a vehicle dynamics performance was shown.

The numerical analysis evaluation method of the vehicles dynamics limit with consideration of this system was shown.

The calculation results of the effect of this system in various types of drivetrain were shown. The application to the front wheels is the most effective for FWD vehicles. On the other hand, the application to the rear wheels is the most effective for RWD and AWD vehicles. The maximum vectoring torque, which is needed for expanding the vehicle dynamics limit, is also described in each case.

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DEFINITIONS

C_f, C_r = Front / Rear Cornering Force

C_{mi} = Maximum Cornering Force of i

$i = fl, fr, rl, rr$ = Wheel Position (Front Left, Front Right, Rear Left, Rear Right)

C_{mr}, C_{ml} = Right / Left Maximum Cornering Force

ΔC_m = Right and left Wheels Total Maximum Cornering Force Difference between Vehicle with Torque Vectoring and without Torque Vectoring

D = Driving Force

D_i = Driving Force of i

D_r, D_l = Right / Left Driving Force

ΔD = Driving Force Difference

G_x = Longitudinal G

$G_{y_{max}}$ = Maximum Lateral G

$G_{y_{fmax}}, G_{y_{rmax}}$ = Maximum Front / Rear Lateral G

H_g = Height of Gravity Center

H_f, H_r = Height of Front / Rear Roll Center

H_s = Distance between Gravity Center and Roll Axis

K_f, K_r = Front / Rear Vehicle Roll Stiffness

L = Wheel Base

L_f, L_r = Distance between Gravity Center and Front / Rear Wheels

m = Vehicle Mass

m_f, m_r = Front / Rear Vehicle Mass

M_g = Total Yaw Moment

M_f, M_r = Yaw Moment Generated by Front / Rear Torque Vectoring

R = Tire Radius

R_r, R_l = Right / Left Tire Maximum Friction Force

R_i = Tire Maximum Friction Force of i

T_e = Engine Torque

T_f, T_r = Front / Rear Distribution Torque

T_v = Vectoring Torque

T_{vf}, T_{vr} = Front / Rear Vectoring Torque

W = Tread

W_f, W_r = Front / Rear Tread

ΔW_x = Load Transfer between Front and Rear Wheels

$\Delta W_{yf}, \Delta W_{yr}$ = Front / Rear Load Transfer between Right and Left Wheels