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DEVELOPMENT OF TORQUE VECTORING CONTROL ALGORITHM FOR FRONT WHEEL DRIVEN DUAL MOTOR SYSTEM AND EVALUATION OF VEHICLE DYNAMICS PERFORMANCE

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ABSTRACT−This study developed a control algorithm of torque vectoring system to improve the handling performance of a green-car and evaluate the performance of vehicle dynamics to improve the controllability and stability. Firstly, this study configured the control algorithm with the supervisory controller that decides the control mode by checking the current driving status of a vehicle, target yawrate calculator that reflects the steady-state and transient-state response characteristics according to the control mode, as well as the reference yawrate calculation, desired yaw moment calculation and transferred torque calculation. The control mode consists of the agile mode that controls the torque vectoring to improve the controllability and the safe mode that controls the torque vectoring to improve stability. Secondly, this study performed the modeling of the dual motor type torque vectoring system and an EV AWD vehicle. Lastly, this study defined the driving test scenario and evaluation method as well as the quantitative performance index for each vehicle test and established the co-simulation environment for the handling test evaluation. This study found that when a vehicle is controlled by applying the torque vectoring system, handling performance was improved according to controllability and safe mode by verifying the simulation.

KEY WORDS : Torque Vectoring System, Handling Performance, Vehicle Dynamics, Dual Motor System, Control Algorithm

NOMENCLATURE

F_x	: longitudinal tire force, N
F_y	: lateral tire force, N
F_z	: vertical tire force, N
a_y	: lateral acceleration, m/s^2
v	: lateral acceleration, m/s
K_{us}	: understeer gradient, deg/g
δ	: steering wheel angle, deg
ψ	: yawrate, deg/s
T	: torque, N·m
M	: moment, N·m

1. INTRODUCTION

1.1. Background of Study

Automobiles are an essential means of transportation that enable a driver to arrive at a destination more quickly, pleasantly, and safely. However, automobiles are causing various social problems such as an increase in fine dust, acceleration of global warming, depletion of fossil energy, etc. In order to solve these problems, the automobile industry is launching various of types of a green-car including EV, HEV, PHEV, FCEV, etc., to minimize the use of existing fossil fuels and to improve fuel efficiency. Recently, consumers are demanding the same performance of driving and braking, ride comfort and handling, active and passive safety, noise and vibration, durability, from a green-car as exist in high performance internal combustion vehicles. In order to satisfy such consumer demands, the automobile industry performs various studies to develop technologies for the elements of high performance green-car. As representative studies, the automobile industry performs studies on the improvement of vehicle dynamics performance of a green-car by improving the acceleration performance using a motor as an auxiliary power source as well as handling performance by applying the torque vectoring technology and the technologies of distributing the driving force to front and rear wheels.

1.2. Trend of Studies

Over a long period of time, the studies have been performed on the control technology to improve vehicle stability. The Anti-lock Braking System (ABS) prevents wheel locking when putting on the brakes and the Traction Control System (TCS) prevents wheel slipping during

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acceleration. While turning a vehicle, the Electronic Stability Control (ECS) limits the engine power or helps maintain vehicle stability by applying brakes to more than one wheel. These systems are very advantageous from the view point of vehicle stability improvement. However, from the view point of driving performance, it is disadvantageous, separately from the intention of the driver, since they reduce the speed of a vehicle in the longitudinal direction by limiting engine power and using the brakes. In order to take measures against such shortcomings, studies began to be performed on the driving torque transfer based torque vectoring system. The turning stability was improved by suppressing the occurrence of understeer of a vehicle reducing the lateral tire force of the rear wheels while maintaining the speed in the longitudinal direction by transferring the driving force from the front wheels to the rear wheels using the center coupling. In addition, the turning stability was improved by suppressing the oversteer transferring the driving torque to the outer side of the turning wheel with low slip while a slip occurs to the inner side of the turning wheel during high speed turning by using the Electronic Limited-Slip Differential (e-LSD) and Torsen Differential. These systems are very useful in that they improve the stability of a vehicle while maintaining the turning speed. However, since the driving torque is transferred to a single direction, limits exist in that the center coupling cannot control the occurrence of oversteer, and the e-LSD and Torsen Differential cannot control understeer. In order to overcome such limits of the system, Active Differential Torque Vectoring was developed which uses a clutch to suppress the occurrence of understeer and oversteer according to a situation by controlling the direction and quantity of the torque transferred to a wheel from the inner turning side to the outer turning side or from the outer turning side to the inner turning side.

Recently, studies have been actively performed on the torque vectoring system that can control regenerative braking using a motor and controls the left and right torques independently. When using a motor, it is advantageous to apply the torque vectoring technology using the rapid response characteristics of the motor and wide control range. As can be seen from Figure 1, this system is available for a wider control range than the active differential and 100 % independent left and right control, and has advantages in that it can control the vehicle in the finer range of understeer and oversteer than the brake system that uses brakes or ESC (van Vliet, 2010). The existing torque vectoring is controlled to improve only the vehicle's controllability, does not consider a transient response characteristics of a vehicle. Therefore, this paper will control torque vectoring using front wheel driven dual motor system for the purpose of improving the vehicle's controllability and stability, and consider a transient response characteristics of a vehicle.

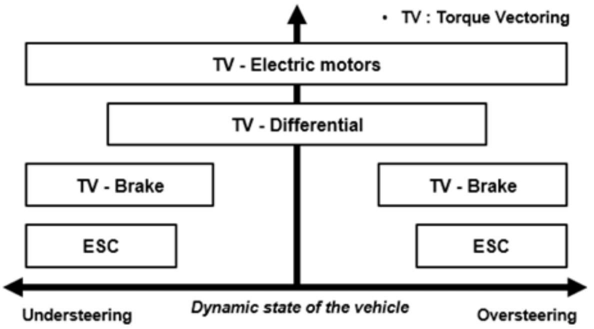


Figure 1. Range of action of various torque vectoring system.

2. TORQUE VECTORING SYSTEM

2.1. Overview of Torque Vectoring

The Torque Vectoring or Active Torque Distribution (ATD) is a system that controls the torque of each wheel variably. The change in wheel torque changes the longitudinal tire force and also changes the lateral tire force due to the Kamm's friction circle principle. Here, the Kamm's friction circle principle is that the total quantity of the friction force that occurs to a tire does not exceed the sum of the vectors for the longitudinal and lateral force as shown in Figure 2. It is used to explain the relation between the forces imposed on the tire in the Torque Vectoring (Heo, 2001).

It is possible to explain the concept of Torque Vectoring through the principle of action. For example, when a vehicle turns to the left, the friction circle of the outer turning wheel increases and the friction circle of the inner turning wheel decreases due to the load transfer. Figure 3 (a) shows the longitudinal tire force of the inner turning wheel reaches the friction limit due to the reduction of the friction circle, showing unstable behavior since the lateral tire force has come to cease to exist. However, as can be seen from Figure 3 (b), when torque is transferred from the inner turning wheel to the outer wheel using Torque Vectoring, the longitudinal tire force of the inner turning wheel decreases, but since the lateral tire force is generated, unstable behavior of the vehicle can be avoid. As a result, when torque vectoring was performed or not, the relation between the longitudinal and lateral tire forces

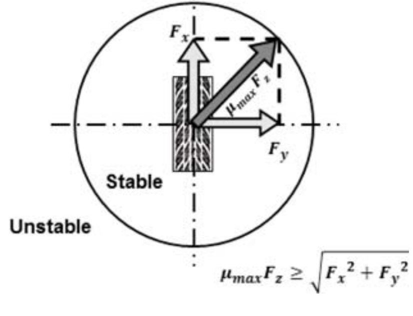
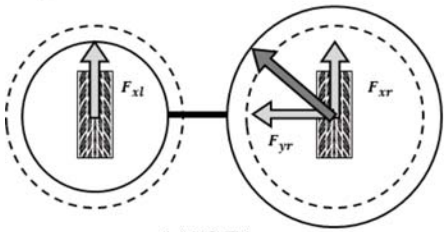
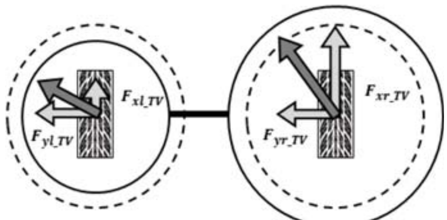


Figure 2. Kamm’s friction circle principle.



(a) NO TV



(b) TV

Figure 3. Torque vectoring principle.

can be arranged as shown in Equations (1) ~ (2) (Ivanov *et al*., 2012). The concept of these equations means that the stability and driving performance of the vehicle must be maintained.

$$F_{yl\_TV} + F_{yr\_TV} = F_{yr} \tag{1}$$

$$F_{xl\_TV} + F_{xr\_TV} = F_{xl} + F_{xr} \tag{2}$$

The handling performance of a vehicle is a term for vehicle dynamics that comprehensively represents the controllability and stability of a vehicle. The controllability ensures a driver's agile steering control of a vehicle within the given range out of the driving course, and the stability means the course stability of a vehicle itself against the external disturbance. Characteristically, the controllability and stability conflict with each other.

The self-steering characteristics can be checked through the steady state cornering test by comparing the variation rate of the steering wheel angle against the lateral acceleration to maintain the circular trace of the wheels. The variation rate of the steering wheel angle against the lateral acceleration maintains a linear zone within the lateral acceleration of approximately 0.4 g. The variation rate of this linear zone is called the understeer coefficient.

Torque vectoring has an advantage in that the self-steering characteristics can be changed according to the purpose to improve the controllability or stability of a vehicle (Folke *et al*., 2010). In Figure 4, TV Agile means that the torque vectoring is controlled to improve the vehicle's controllability, and TV Safe means that the torque vectoring is controlled to improve the vehicle's stability. If the torque vectoring is controlled to improve controllability, the understeer coefficient of a vehicle decreases and the maximum lateral acceleration increases. The decrease in the understeer coefficient means that the driver's steering input to maintain the given course has decreased, and the increase in the maximum lateral acceleration means that the vehicle's stability margin has increased. In addition, increasing the vehicle's understeer coefficient by controlling the torque vectoring to improve stability means that the course stability of the vehicle itself has increased against the external disturbance.

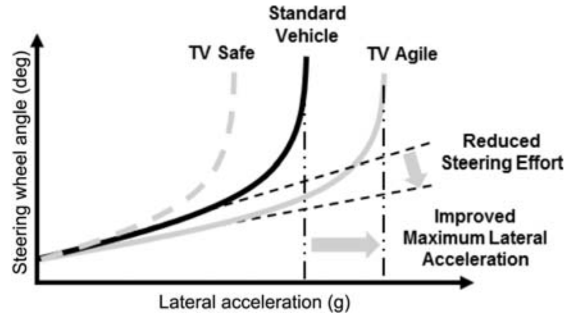


Figure 4. Purpose of torque vectoring.

This study performed the modeling of the dual motor type torque vectoring system to improve the handling performance of a green-car, and designed and applied the torque vectoring control algorithm. In addition, the purpose of this study is to configure the simulation environment to evaluate the torque vectoring performance and analyze the performance in the view point of handling performance of a vehicle.

2.2. Torque Vectoring Control Algorithm

The torque vectoring control algorithm examines the current driving status of a vehicle and calculates the target yawrate according to the purpose to improve the controllability or stability. In addition, it is configured as shown in Figure 5 so that the required compensated yaw moment can be calculated based on the difference between the reference yawrate and target yawrate and that the direction and quantity of the yaw moment can be controlled by generating driving torque for the left and right wheels.

The supervisory controller that examines the current driving status of a vehicle decides the torque vectoring control mode by comparing the maximum yawrate within the normal driving range and the friction limit range with the actual vehicle yawrate according to its driving speed (Crolla, 2015). The normal driving range means the yawrate value in the steady state according to the speed which considers the maximum steering angle, and it is as presented by Equation (3) which applies the formula for the Steady-State Yaw Magnitude Ratio. Equation (3) shows how wheelbase l, understeer coefficient of uncontrolled vehicle K_{us} are related. If the actual vehicle yawrate value does not exist within the normal driving range, it can be judged to be in the unstable state.

$$\left|\dot{\psi}_{\mathrm{Normal\_Driving}}\right| \le \frac{v}{l + K_{us} \cdot v^2}\delta_{\max} \tag{3}$$

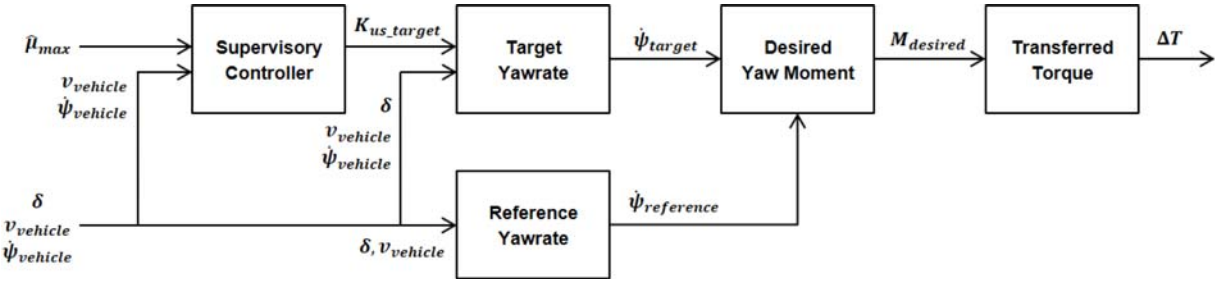


Figure 5. Block diagram of torque vectoring algorithm.

The friction limit range means the yawrate value according to the speed that considers the lateral stability, and it is as presented by Equations (4) ~ (5) that arranged the relation between the maximum lateral force and friction force. In addition, even in the case of the friction limit range, if the actual vehicle yawrate value does not exist within the friction limit range, it can also be judged to be in the unstable state. This study considers only two types of roads including a road with a high friction surface such as a dry asphalt road and a road with a low friction surface such as a road covered with snow, and performed design so that the estimated value would be used for the road friction coefficient.

$$m \cdot a_y \le m \cdot \hat{\mu} \cdot g \tag{4}$$

$$\left|\dot{\psi}_{\text{Friction\_Limit}}\right| \le \frac{\hat{\mu} \cdot g}{v} \tag{5}$$

The torque vectoring control mode consists of the Agile Mode and Safe Mode. An aimed vehicle's understeer coefficient according to each mode is calculated differently.

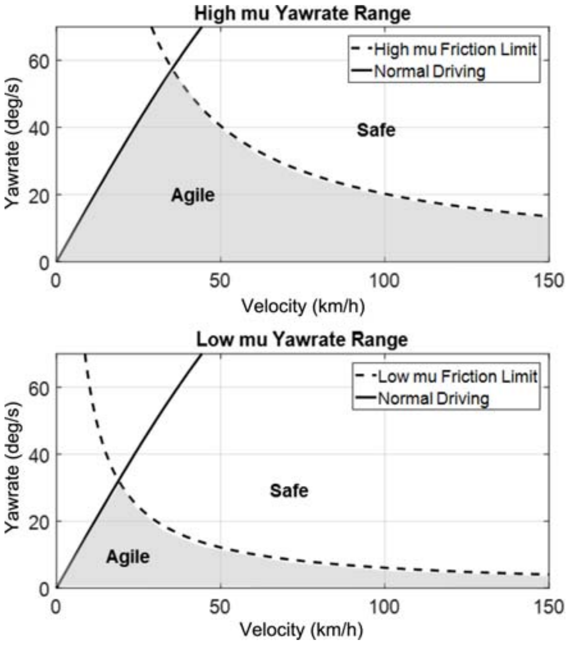


Figure 6. Yawrate range of supervisory controller.

If the actual vehicle yawrate value exists in the intersection of the normal driving range and friction limit range, the vehicle is judged to be in the Agile Mode as highlighted in gray color in Figure 6 since the vehicle can drive stably. However, if the actual vehicle yawrate value does not exist in the intersection, the vehicle's mode is decided to be in Safe Mode since its behavior is in an unstable state.

Once the target understeer coefficient of a vehicle is calculated according to the Agile or Safe Modes, the target yawrate for the torque vectoring is calculated. The target yawrate is designed to be configured as shown in Figure 7 so that it can be calculated by reflecting the response characteristics in the steady state and transient state of a vehicle (Bünte *et al*., 2014).

The target steady state yawrate reflecting the steady state response characteristics is calculated using Equation (6) which applies the Steady-State Yaw Magnitude Ratio of a vehicle against the steering input for circular driving at constant speed. The target understeer coefficient included in this equation is a very important parameter in calculating the target yawrate and it is calculated from the supervisory controller.

$$\dot{\psi}_{\text{target\_s}} = \frac{v}{1 + K_{\text{us\_target}} \cdot v^2}\delta \tag{6}$$

The transient response characteristics of a vehicle related to the yawing motion response characteristics and amplification ratio is reflected by configuring a yawrate filter. The yawrate filter is configured through several steps as follows:

Configure the motion equation of the 2DOF bicycle model as a transfer function, as shown in Equation (7) through Laplace transform. In this equation, T_z, ω_n and ζ mean a time constant, an undamped yaw natural frequency

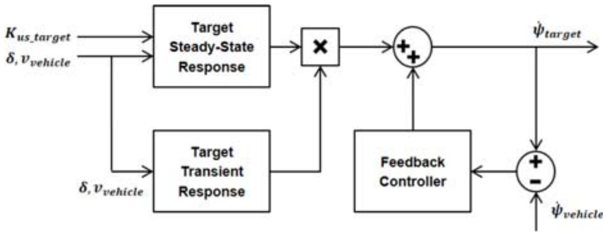


Figure 7. Target yawrate calculation.

and yaw damping ratio, respectively.

$$G_{\delta_{\mathrm{f}}\rightarrow\dot{\psi}}(s)=\left(\frac{\dot{\psi}}{\delta}\right)_{\mathrm{s.s}}\cdot\frac{1+T_{\mathrm{z}}s}{1+\frac{2\zeta}{\omega_{\mathrm{n}}}s+\frac{1}{\omega_{\mathrm{n}}^{2}}s^{2}} \tag{7}$$

And, in order to set the target transient state response characteristics, transform the transfer function as shown in Equation (8) by adding three tuning parameters (λ_{D}, λ_{S}, λ_{Z}).

The λ_{D}, λ_{S} and λ_{Z} are tuning parameters relating to damping ratio corresponding to magnitude ratio, response time, and dynamic response to the input, respectively.

$$G_{\delta_{\mathrm{f}}\rightarrow\dot{\psi}_{\mathrm{target\_t}}}(s)=\left(\frac{\dot{\psi}}{\delta}\right)_{\mathrm{s.s}}\cdot\frac{1+\frac{T_{\mathrm{z}}}{\lambda_{\mathrm{z}}\lambda_{s}}s}{1+2\frac{1-\lambda_{\mathrm{D}}(1-\zeta)}{\lambda_{s}\omega_{\mathrm{n}}}s+\frac{1}{\lambda_{s}^{2}\omega_{\mathrm{n}}^{2}}s^{2}} \tag{8}$$

In the above equation, the $(\dot{\psi}/\delta)_{\mathrm{s.s}}$ means the steady state response value. Therefore, if a linear filter is configured as show in Equation (9) so that this steady state response value can be offset, it is possible to reflect only the transient state response characteristics.

$$\Gamma_{\delta_{\mathrm{f}}\rightarrow\dot{\psi}_{\mathrm{target\_t}}}(s)=\frac{G_{\delta_{\mathrm{f}}\rightarrow\dot{\psi}_{\mathrm{target\_t}}}(s)}{G_{\delta_{\mathrm{f}}\rightarrow\dot{\psi}_{\mathrm{target\_t}}}(0)} \tag{9}$$

The target yawrate is calculated by multiplying the yawrate value that reflects the steady state response characteristics and the filter value that reflects the transient state response characteristics. This study designed the feedback controller so that the target yawrate value can be compensated by comparing the actual vehicle yawrate value. In the case of the reference yawrate, a yawrate of a vehicle that does not perform control was calculated using the 2DOF bicycle model, and the direction and quantity of the required compensated yaw moment was calculated using Equation (10) based on the difference from the target yawrate. In addition, by calculating the driving torque of the left and right wheels that can generate the required compensated yaw moment using Equations (11) ~ (12), torque was generated from the left and right motors.

$$\begin{aligned}M_{\mathrm{desired}}=&\frac{I_{\mathrm{z}}}{\cos(\delta)}(\ddot{\psi}_{\mathrm{target}}+\dot{\psi}_{\mathrm{target}}-\dot{\psi}_{\mathrm{reference}})+\\&\frac{l_{\mathrm{r}}}{\cos(\delta)}(F_{\mathrm{yrr}}+F_{\mathrm{yrl}})-l_{\mathrm{f}}(F_{\mathrm{yfr}}+F_{\mathrm{yfl}})-\\&\frac{l_{\mathrm{w}}}{2\cos(\delta)}(F_{\mathrm{xrr}}-F_{\mathrm{xrl}})\end{aligned} \tag{10}$$

$$T_{\mathrm{r}}=\frac{1}{2}T_{\mathrm{mot}}+\Delta T$$

$$T_{\mathrm{l}}=\frac{1}{2}T_{\mathrm{mot}}-\Delta T \tag{11}$$

$$\Delta T=I_{\mathrm{W}}(\dot{\omega}_{\mathrm{fr}}-\dot{\omega}_{\mathrm{fl}})+2\frac{r_{\mathrm{dyn}}}{l_{\mathrm{w}}}M_{\mathrm{desired}} \tag{12}$$

In order to verify the performance of the torque vectoring system according to the Agile and Safe Modes, this study set the control target as follows:

The target understeer coefficient was calculated by reducing the understeer coefficient by 30 % in the Agile Mode and by increasing the understeer coefficient by 30 % in the Safe Mode. In addition, regardless of the control mode, both the transient response characteristics of the vehicle with regard to the yawing motion response characteristics and amplification ratio were set to be improved.

3. HANDLING PERFORMANCE EVALUATION OF TORQUE VECTORING SYSTEM

3.1. Establishment of Integrated Simulation Environment

This study established an integrated simulation environment in order to evaluate the steering performance of the torque vectoring system. This study used an EV AWD vehicle as a vehicle model, and configured a powertrain by modeling dual motors (25 kW) for driving and torque vectoring on the front wheel and a motor (50 kW) for driving on the rear wheel as shown in Figure 8. The driving force of the front and rear wheels were made to have a fixed distribution ratio of 4 to 6. Modeling of the vehicle and torque vectoring system was performed using Amesim from the SIEMENS, and the torque vectoring control algorithm was designed using Matlab/Simulink.

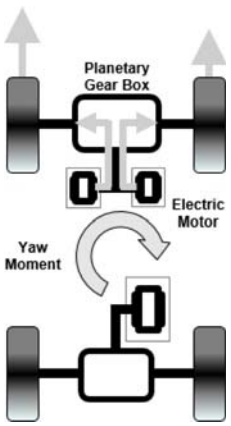


Figure 8. Dual motor type torque vectoring system.

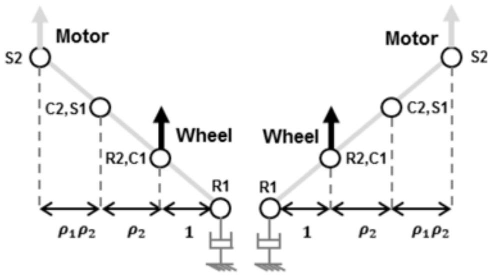


Figure 9. Combined lever diagram of dual motor type torque vectoring system.

This study selected the dual motor type torque vectoring system as shown in Figure 9. It is composed so that the torque generated from the dual motors can be transferred to each wheel through the planetary gear and that the yaw moment required by a vehicle can be generated by having the left and right wheels generate torque independently.

3.2. Simulation Result

In order to evaluate the handling performance of the torque vectoring system, this study defined the driving test scenario and evaluation method as well as the quantitative performance index by test item referring to the regulations of ISO. All result graphs show Standard Vehicle when torque vectoring was not performed, Agile Mode for the control of the Torque Vectoring Controllability, and Safe Mode for the control of Torque Vectoring Stability.

3.2.1. Steady State Maneuver Simulation

Steady State Cornering (SSC) is a driving test method to examine the vehicle's self-steering characteristics according to the criteria of (International Organization for Standardization, 2012). This study performed the simulation on the condition that an additional steering wheel angle is inputted to maintain the cornering radius of 50 m while increasing the driving speed of a vehicle. This study selected the understeer coefficient which is the variation rate of the steering wheel angle according to the lateral acceleration at lateral acceleration of approximately 0.4 g and the maximum lateral acceleration as Performance Index (PI). Figure 10 show the steady state cornering simulation result.

When the torque vectoring was controlled to improve the controllability, the understeer coefficient was reduced, reinforcing the weak understeer characteristics. This means that the controllability of a vehicle has been improved since it can be judged that the driver's steering effort was reduced thus requiring less steering wheel manipulation during cornering. And the limit lateral acceleration of a vehicle was increased. This means that the stability margin of a vehicle has been improved under extreme driving conditions. When the torque vectoring was controlled to improve the stability, the understeer coefficient increased, thus reinforcing the strong understeer characteristics. This means that the course stability of a vehicle itself has increased against the external disturbance.

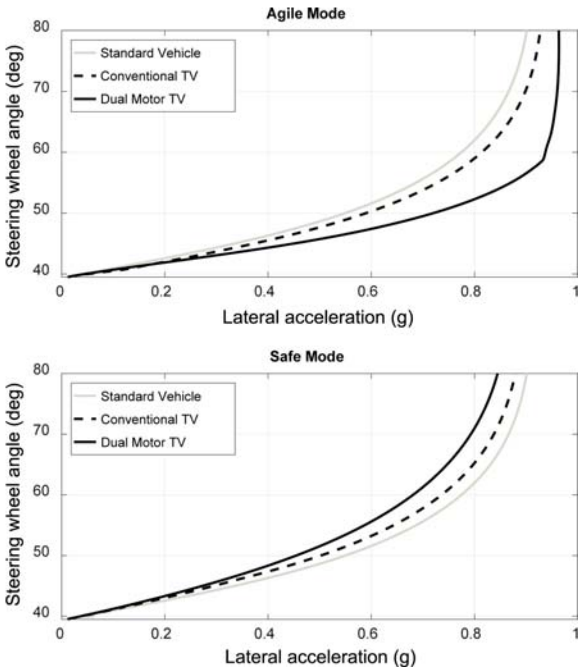


Figure 10. Steady state cornering result.

3.2.2. Transient State Maneuver Simulation

The J-turn (Step Steering Input) is a driving test method to examine the transient response characteristics of a vehicle according to the (International Organization for Standardization, 2011) standard. This study performed simulation on the condition that the vehicle's driving speed is maintained constantly at 100 km/h and that the steering wheel angular velocity of 500 deg/s corresponding to the steady state lateral acceleration of 0.6 g is inputted. The yawrate response time, overshoot ratio were selected as performance indexes. Figure 11 shows the J-turn simulation result.

When the torque vectoring was controlled to improve the controllability and stability, both the vehicle's yawrate response time and overshoot ratio were reduced. This means that the vehicle's maneuverability was improved since it can be judged that the vehicle can reach the stable driving track quickly with the small yawing motion of a vehicle.

Slalom is a driving test method to examine the transient state response characteristics of a vehicle including the

Table 1. Normalized performance index of steady state maneuver simulation.

	Standard Vehicle	Agile Mode Conventional TV	Agile Mode Dual Motor TV	Safe Mode Conventional TV	Safe Mode Dual Motor TV
SSC Kus	1	0.95	0.70	1.16	1.30
SSC Max.ay	1	1.04	1.07	0.99	0.97

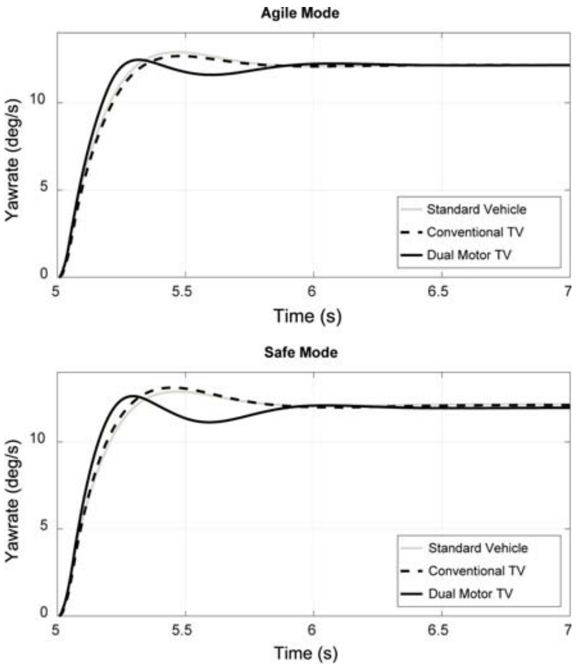


Figure 11. J-turn result.

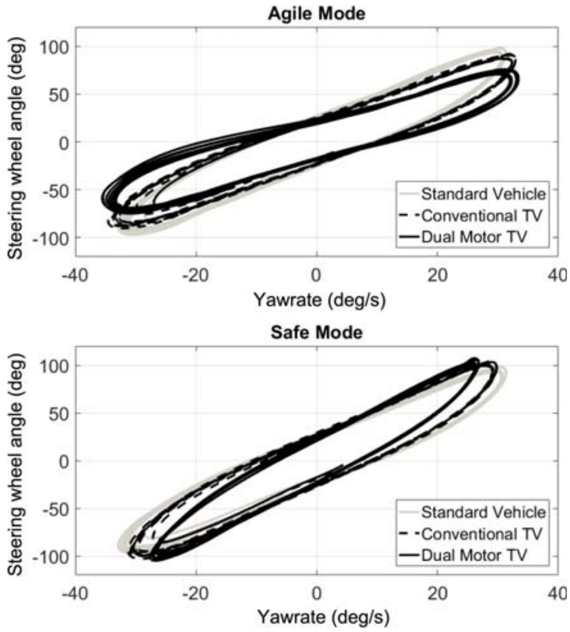


Figure 12. Slalom result.

driving course follow-up performance, agility, etc. This study performed the simulation on the condition that the vehicle's driving speed is maintained constantly at 70 km/h and that the additional steering wheel angle to pass cone consisting of 18 m intervals is inputted. The Peak to Peak of steering wheel angle, the Peak to Peak of yawrate, etc., were selected as performance indexes. Figure 12 shows the Slalom simulation result.

When the torque vectoring was controlled to improve the controllability, the Peak to Peak of steering wheel angle was reduced. This means that the vehicle's controllability has improved since the driver's steering wheel manipulation to maintain the driving course is reduced. And the vehicle's Peak to Peak of yawrate maintained the same level. This means that the vehicle's stability was maintained. When the torque vectoring was controlled to improve the stability, the Peak to Peak of steering wheel angle increased and the vehicle's Peak to Peak of yawrate value was reduced. This means that the vehicle's stability was improved even though a driver frequently manipulates the steering wheel to maintain the driving course.

3.2.3. Circuit Driving Simulation

The circuit driving as Figure 13 is carried out to demonstrate the effectiveness of the torque vectoring was controlled to improve the controllability for a longer period of time. All plot show the circuit simulation result of standard vehicle (No control) and dual motor type torque vectoring system (With Control). As shown in ① and ② conering course of Figure 14 and 15, the steering wheel angle was reduced and the yawrate value was increased little bit, but maintained the same level stability. When look at the whole circuit course, the reduction of the RMS value of steering wheel angle means that the vehicle's

Table 2. Normalized performance index of transient state maneuver simulation.

	Standard Vehicle	Agile Mode Conventional TV	Agile Mode Dual Motor TV	Safe Mode Conventional TV	Safe Mode Dual Motor TV
J-turn Yawrate Response Time	1	1.05	0.84	0.90	0.57
J-turn Yawrate Overshoot Ratio	1	0.67	0.40	1.32	0.63
Slalom SWA Pk to Pk	1	0.93	0.75	1.06	1.08
Slalom Yawrate Pk to Pk	1	1.05	1.06	0.95	0.86

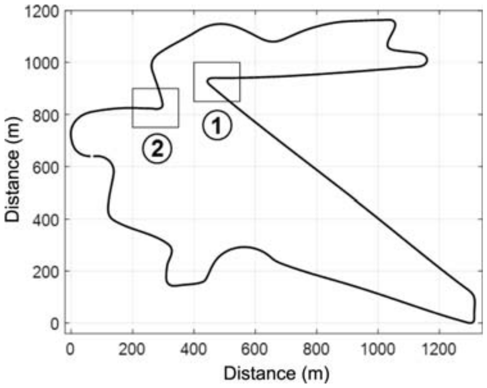


Figure 13. Yeongam international circuit.

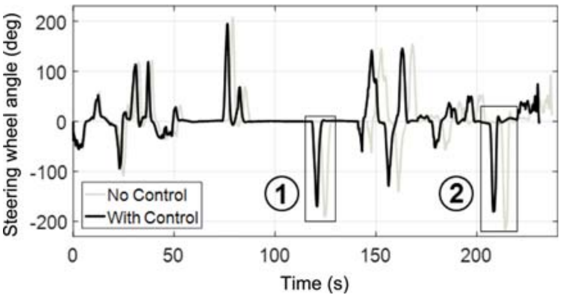


Figure 14. Steering wheel angle of circuit result.

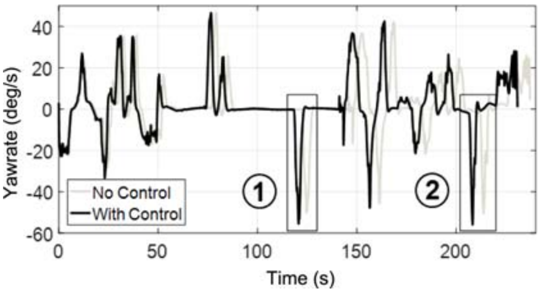


Figure 15. Yawrate of circuit result.

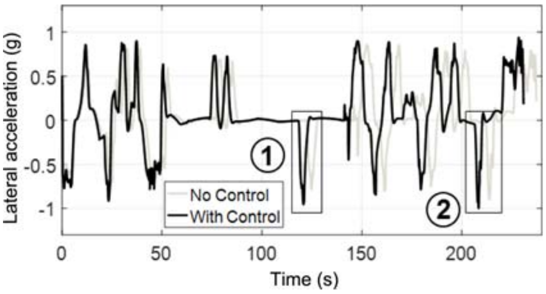


Figure 16. Lateral acceleration of circuit result.

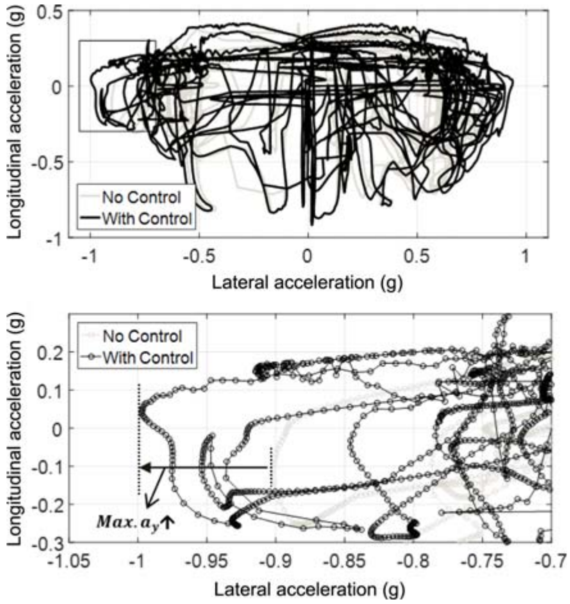


Figure 17. G-G diagram of circuit result.

Table 3. Normalized performance index of circuit driving simulation.

	No Control	With Control
Circuit SWA RMS	1	0.88
Circuit Yawrate RMS	1	1.02
Circuit Lap Time	1	0.97
Circuit Max. ay	1	1.11

controllability has improved since the driver's steering wheel manipulation to maintain the driving course is reduced and maintaining the RMS value of yawrate at the same level means that the vehicle's stability was maintained. The time to pass the circuit course was also reduced, which means that a vehicle has passed the given course with agility. As shown in Figure 17, which display longitudinal acceleration versus lateral acceleration, the maximum lateral acceleration increases. The increase in the maximum lateral acceleration means that the vehicle's stability margin has increased and better turning capability are achieved by activating the torque vectoring controllability.

4. CONCLUSION

The study performed research on the torque vectoring system in order to improve the handling performance of a green-car. This study modeled a vehicle and torque vectoring system and designed the torque vectoring control algorithm. In addition, it performed handling test simulations by establishing an integrated simulation environment, and verified the torque vectoring performance according to the Agile and Safe Modes. The conclusions obtained regarding the above important details of the study are as follows:

(1) This study designed a torque vectoring control algorithm that reflects the supervisory controller which decides the torque vectoring control mode by examining the current driving status of a vehicle as well as the torque vectoring control algorithm which reflects the steady state and transient state response characteristics.

(2) This study performed modeling of an EV AWD vehicle which applies the dual motor type front torque vectoring system.

(3) This study defines the driving test scenario and evaluation method to verify the torque vectoring performance as well as the quantitative performance indexes by test item.

(4) This study verified that the vehicle's handling performance was improved according to the Agile and Safe Modes by evaluating some case simulations.

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