

Evaluation of an intuitive 4WD drift assist control concept in a driving simulator

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ABSTRACT

In this paper, we present a concept of drift assist control for a 4-Wheel-Drive (4WD) electric vehicle that allows independent wheel torque control, aiming at an intuitive interaction with the average human driver. The concept is evaluated through a driver-in-loop trial using a driving simulator. Starting with a 4WD drift equilibrium analysis, we demonstrate the necessity of incorporating the throttle input for sideslip control and the idea of restricting the sideslip rate in order to assist the driver in stabilising the vehicle in drifting. Subsequently, we design a sideslip rate and yaw rate controller according to the desired sideslip angle from the driver using torque vectoring. To evaluate our control concept, a circular track is built in Cranfield University's driving simulator based on the IPG CarMaker software. 34 participants were recruited to perform two drifting tasks, including the transition from normal cornering to drifting and regulating the sideslip under different configurations of sideslip damping rate and steering wheel feedback torque. Through subjective questionnaires and objective evaluation of vehicle states, the results show that our concept can assist the driver in intuitively controlling the vehicle during drifting.

ARTICLE HISTORY

Received 8 May 2024
Revised 20 March 2025
Accepted 26 March 2025

KEYWORDS

Drift assist control; torque vectoring; driver-in-loop trial; vehicle dynamics

Introduction

Cornering at a high sideslip angle with the direction of yaw rate opposite to the steering direction has been known as 'drifting' with 'counter-steer' [1] which normally could only be performed by experienced drivers, starting with destabilising the rear axle with high sideslip ratio followed by subtle throttle control and a correct amount of counter-steering [2]. The art of drifting is all about friction utilisation at the front and rear tyres near their saturation limit [3]. The challenge of drift control is caused by its unstable equilibrium [4–6], which requires expert skills from the human driver or assist by dedicated control systems.

Previous studies have been extensively focused on Rear-Wheel-Drive (RWD) Autonomous Vehicle (AV) drifting [7]. After calculating the drift equilibria as target with a single-track [8–10] or double-track vehicle model [11], various methods (proportional feedback control in Ref. [12,13], LQR in Ref. [11,14–17], MPC in Ref. [18–23]) have been

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applied to stabilise the vehicle at the equilibrium point [24,25], or to consider trajectory tracking [26–28] along a complex shape track [22,29,30], normally by means of controlling the steering and the rear slip ratio, or considering additional actuators like front brakes [31] or torque vectoring [32].

Drift assist control, where the driver maintains the authority of the steering in the context of Advanced Driver Assist System (ADAS), has been introduced by several high-performance vehicles like McLaren [33] and BMW [34] and allows the vehicle to operate beyond the limits of stability control. By utilising actuators like clutch-actuated active differentials, more torque can be allocated to either side of the rear wheels for power oversteer [35]. Moreover, [36] proposes a stability envelope-based framework with throttle and steering torque intervention, to assist the driver perform drifting against the risks of spinning or violating track boundaries. However, it still requires skills and proper driver reaction at any time [34]. One of the reasons is that while the throttle could be assisted by the aforementioned control to saturate the rear axle properly, the lateral force of the front is directly controlled by the driver through steering. Furthermore, the linear relationship between steering and sideslip angle at the drift equilibria of a given speed [8] requires proper coordination of steering and throttle from the driver, despite having assist control.

Unlike RWD, for 4-wheel drive (4WD) vehicle, the authors in Ref. [37] have discovered the secondary drift equilibria. Similar results and the effects of front-rear torque distribution on drift equilibria are also discussed in Ref. [6], hence there are more flexibilities in the hierarchical controller design [38,39]. Specifically, in contrast to recent RWD drift control studies that benefit from accurate tyre [40] and vehicle [23] modelling through neural networks, for a 4WD vehicle that allows independent wheel torque control, the system is over actuated therefore a simple feedback controller is able to regulate the motion without prior knowledge of drift equilibrium [23,41–43]. Similarly, for production vehicles without accurate tyre model for equilibrium calculation as a reference, [44–46] deploys a relatively simple control structure that uses steering to control yaw rate and throttle for sideslip [44] or just a fixed slip ratio [45,46]. In recent studies, [6] applies a simple PD-controller and [47] applies reinforced learning in controlling the torque of front/rear axle to stabilise the sideslip meanwhile the steering is controlled by human drivers.

Considering the benefits offered by 4WD with independent wheel torque allocation in terms of drift control, as well as the professional driving skills required by the existing drift assist control system, we aim to investigate the potential for creating an intuitive drift assist control concept for the average drivers.

To validate vehicle control systems with driver-in-loop, driving simulators have been widely applied for traction control [48], torque vectoring [49], power steering [50] and transmission [51] evaluation. Besides objective evaluation, participants are also asked to fill out questionnaires and rate ADAS systems in terms of stability [52], safety [53], steering comfort [54] and ride comfort [55]. Furthermore, driving simulators could also help study the driver's behaviours in scenarios like tunnels [56], intersections [57] and car following [58], as well as driver's preference in ADAS interface [59,60].

Based on the analysis above, this paper utilises a driving simulator to assess an intuitive drift assist control system for a 4WD vehicle with independent wheel torque control. Starting with drift equilibrium analysis, we highlight the importance of introducing throttle input for sideslip control and the concept of limiting sideslip rate to aid the driver in stabilising the drifting vehicle. Following this, we design a sideslip and yaw rate controller

using torque vectoring, without relying on prior equilibrium data. To evaluate our concept, a circular track is built in CarMaker and 34 participants are recruited to perform two tasks: (a) the transition from normal cornering to drifting and (b) increasing the sideslip using throttle, across nine different sideslip rate and steering feedback torque configurations. Using both subjective and objective evaluation, we demonstrate that our concept can assist the driver in controlling the vehicle intuitively during drifting, particularly with low sideslip rate and high torque feedback on the steering wheel.

Equilibria analysis for 4WD drifting

In prior research about RWD drifting equilibrium, the equations to describe the vehicle motions displayed in (1) involve five variables (the longitudinal speed v_x , yaw rate r , sideslip angle β , wheel steering angle δ , and longitudinal force of rear axle F_{xr}), while the vehicle mass m , yaw inertia I_z , and distance from axles to the centre of gravity (CoG) l_f, l_r are known constants, the lateral force for front and rear axle F_{yf}, F_{yr} are derived according to the sideslip. In equilibrium states where all three dynamic equations are set to zero, it is necessary to have knowledge of two out of the five variables (typically v_x and δ for an RWD vehicle) in order to solve the equations.

$$\begin{aligned}\dot{v}_x &= \frac{F_{xr} - F_{yf}\sin(\delta)}{m} + rv_x\beta \\ \dot{r} &= \frac{l_f F_{yf}\cos(\delta) - l_r F_{yr}}{I_z} \\ \dot{\beta} &= \frac{F_{yr} + F_{yf}\cos(\delta)}{mv_x} - r\end{aligned}\quad (1)$$

Solving the drift equilibria with a 4WD vehicle dynamics model

Nevertheless, the equations mentioned above are no longer applicable for a 4WD vehicle with independent torque control on each wheel. As in (2) and Figure 1, there are a total of eight variables present: speed v , yaw rate r , sideslip angle β , wheel steer angle δ , and longitudinal force of each wheel F_{xij} ($i = f, r; j = l, r$). Consequently, in order to solve the three equations, five variables must be provided.

$$\begin{aligned}\dot{v} &= \frac{1}{m}[(F_{xfl} + F_{xfr})\cos(\delta - \beta) - (F_{yfl} + F_{yfr})\sin(\delta - \beta) \\ &\quad + (F_{xrl} + F_{xrr})\cos\beta + (F_{yrl} + F_{yrr})\sin\beta] \\ \dot{r} &= \frac{1}{I_z} \left\{ [(F_{xfl} + F_{xfr})\sin\delta + (F_{yfl} + F_{yfr})\cos\delta]a - [F_{yrl} + F_{yrr}]b \right. \\ &\quad \left. + [(F_{xfr} - F_{xfl})\cos\delta - (F_{yfr} - F_{yfl})\sin\delta + (F_{xrr} - F_{xrl})]\frac{w}{2} \right\} \\ \dot{\beta} &= \frac{1}{mv}[(F_{xfl} + F_{xfr})\sin(\delta - \beta) + (F_{yfl} + F_{yfr})\cos(\delta - \beta) \\ &\quad - (F_{xrl} + F_{xrr})\sin\beta + (F_{yrl} + F_{yrr})\cos\beta] - r\end{aligned}\quad (2)$$

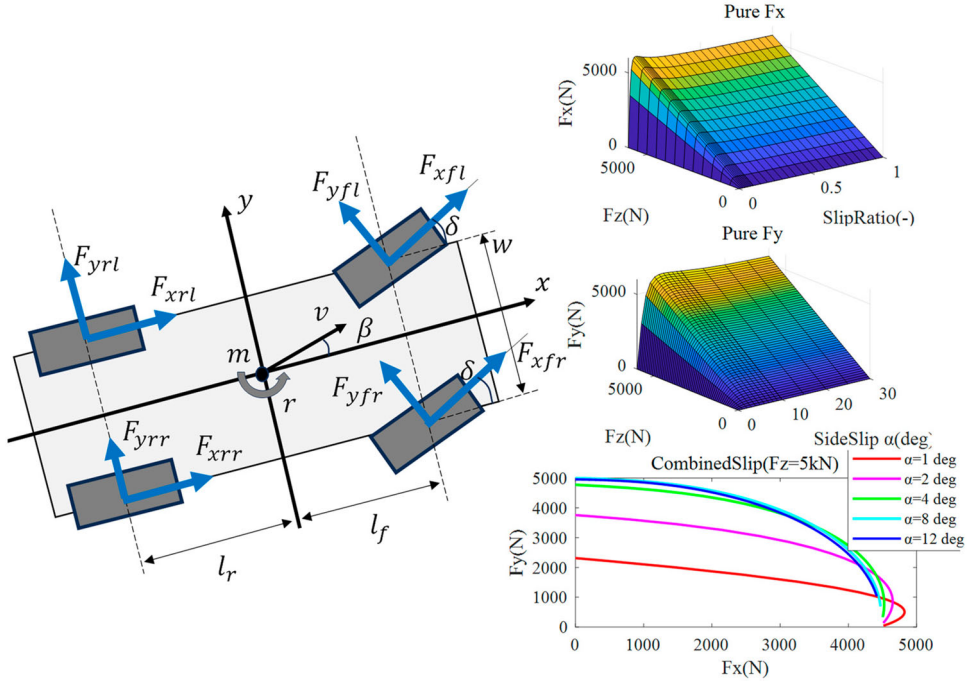


Figure 1. The 4WD vehicle model and tyre model for drift equilibria calculation.

Table 1. Vehicle model parameters (based on a generic vehicle model from CarMaker).

Parameters	Value	Unit
Total mass m	1645	kg
Distance from CoG to front axle l_f	1475	mm
Wheelbase $l_f + l_r$	2750	mm
Wheel track w	1600	mm
CoG height h	400	mm

Therefore, based on the methods of [37], we construct a 4WD drift equilibrium map utilising specified δ and slip ratios s_{rij} for tyres. The forces F_{xij} , F_{yij} of the tyres in (2) are determined using the Magic Formula tyre model [61], written as (3) before considering combined slip (Figure 1), in which μ is the friction coefficient, B_{Fi} , C_{Fi} are tyre coefficients and F_{zij} is the vertical load of tyre calculated ignoring the suspension effects.

$$\begin{aligned}
 F_{xi} &= \mu F_{zi} \sin(C_{Fx} \operatorname{atan}(B_{Fx} s_{ri})) \\
 F_{yi} &= \mu F_{zi} \sin(C_{Fy} \operatorname{atan}(B_{Fy} \alpha_i))
 \end{aligned} \tag{3}$$

The above configurations result in the three functions (2) having only three unknown variables (v, r, β), and we employ the *fsolve* function within Matlab to solve them with $\dot{v} = \dot{r} = \dot{\beta} = 0$ according to the following vehicle parameters (Table 1), also under the condition of a left corner ($r > 0$) with counter-steering ($\delta < 0$).

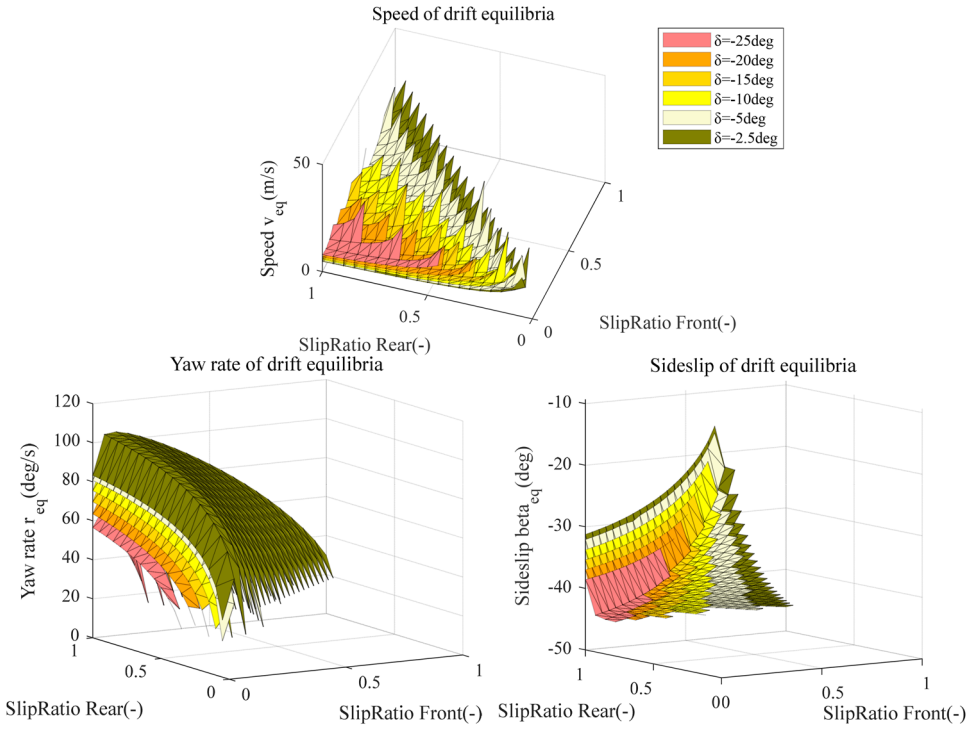


Figure 2. The 4WD drift equilibria in a left corner with specified steering angle and slip ratios for the axles.

The effects of counter-steering angle on the drift equilibria

Assume the wheels on the same axle have equal slip ratio as $s_{rfl} = s_{rfr} = s_{rf}$, $s_{rll} = s_{rrl} = s_{rr}$, the solved equilibria are shown in Figure 2, with each steering angle's results distinguished by a unique colour. In general, increasing the amount of counter-steering results in a narrowed equilibrium area where the slip ratio for the rear axle s_{rr} is high, and the front s_{rf} is low. Our explanation for this narrowed area is as follows: Firstly, in agreement with previous studies, low sideslip at the front axle [2,6] (and unsaturated lateral force compared to the rear as discussed in Ref. [3,9]) is always observed during drifting, therefore the equilibrium sideslip at the centre of gravity (CoG) will increase together with counter-steering (as shown in Figure 2, Figure 3 and also [6,8,9]) kinematically to guarantee low sideslip of the front. The increased CoG sideslip also requires more longitudinal force from the rear to work as centripetal force at the equilibrium state, therefore for the narrowed area the rear slip ratio s_{rr} is higher. Secondly, more lateral force from the front is expected as centripetal force at the equilibrium of higher counter-steering and sideslip, so the variation range of s_{rf} is reduced to prevent the front from saturation.

Interestingly, it is worth noting that the equilibrium point can be shifted on the surface of a given steering angle in Figure 2 by adjusting the slip ratio s_{rf} , s_{rr} , which means a possibility to uphold the desired yaw rate r_{eq} or the sideslip angle β_{eq} even after the driver alters the steering input. However, it is impossible to maintain both of these states simultaneously.

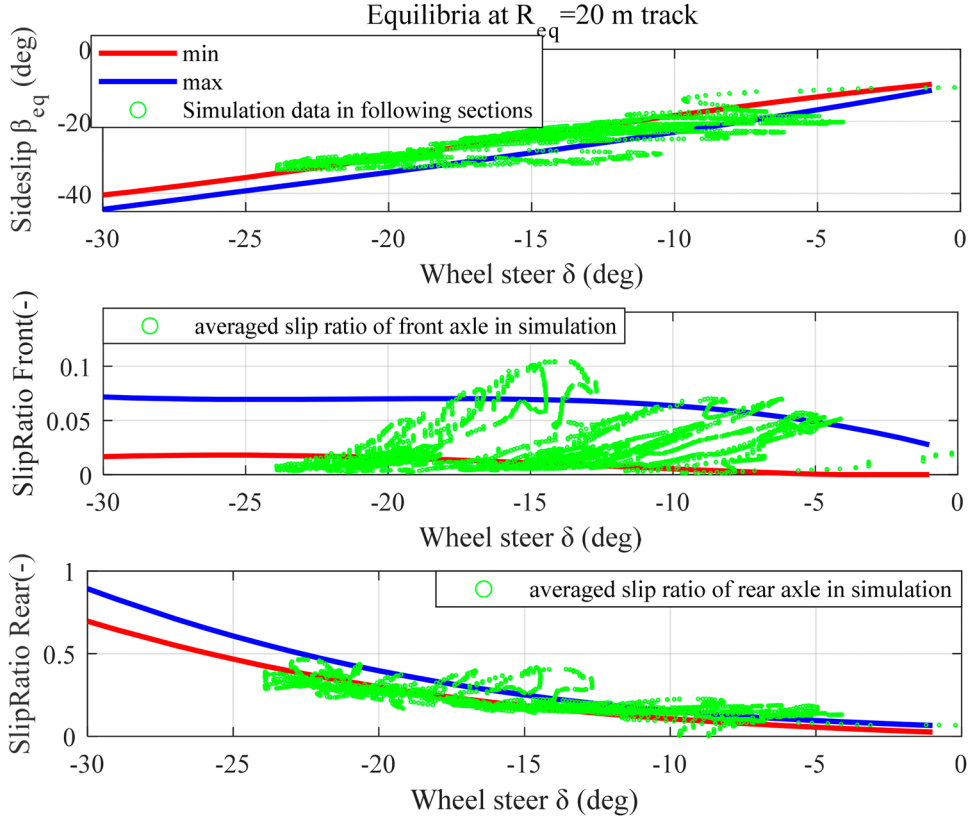


Figure 3. The drift equilibria with fixed trajectory radius $R_{eq} = 20$ m.

For instance, when the steering increases from -10 to -25 deg (Figure 2), in order to prevent yaw rate r_{eq} from reducing, s_{rr} has to increase and s_{rf} to decrease; but for sustaining sideslip β_{eq} , the trend is opposite that s_{rr} needs to decrease and s_{rf} needs to increase.

This contradiction firstly indicates that the steering effects on equilibrium states cannot be fully cancelled by altering the slip ratio of front and rear axle. Additionally, and most importantly, it suggests the necessity of incorporating another driver input (the throttle) besides steering in order to decouple the effects of steering on equilibrium yaw rate and sideslip. Henceforth, in contrast to autonomous drifting studies that coordinate throttle and steering to track the target drift equilibrium states (i.e. [11,19]), in the subsequent sections, the target sideslip is interpreted according to throttle and regulated by torque vectoring, and the steering angle ideally only contributes to yaw rate, which remains consistent with normal driving, in order to make the system intuitive.

The drift equilibria with fixed trajectory radius

Upon analysing the influence of counter-steering angle on drift equilibria, we further consider the equilibrium trajectory with radius $R_{eq} = \frac{v_{eq}}{r_{eq}}$ and solve the equilibrium equations (2) with the same method as the last section, but this time for β_{eq} , s_{rf} and s_{rr} after defining R_{eq} , v_{eq} and δ . As shown in Figure 3, within a circular track of 20 m radius, the control of

axle slip ratios s_{rf} , s_{rr} only provides limited flexibility (area between the two lines) in the equilibrium sideslip β_{eq} , which is primarily determined by the steering angle δ .

Furthermore, for our suggested concept of utilising throttle for sideslip control, the preceding analysis implies that in a track of constant radius, the driver must coordinate the steering with sideslip to uphold the radius. For example, when the driver is demanding more sideslip from torque vectoring, he/she also has to perform more counter-steer in order to stay on track (Figure 3). This is a counter-intuitive behaviour which requires expert driving skills, particularly when the sideslip increases too fast. In this case, some drivers may struggle to counter-steer promptly and accurately. Hence, we suggest restricting the sideslip rate in order to allow the driver reaction time to counter-steer.

The design of the drift controller

After the equilibrium analysis, we identify the following objectives for the drift controller design: Firstly, the throttle should be utilised to regulate the sideslip angle. Secondly, it is crucial to restrict the sideslip rate to allow the driver reaction time for counter-steering when sideslip increases. Besides, in contrast to previous studies, due to independent torque control for all four wheels, in our study the system is over actuated therefore prior knowledge of drift equilibrium is unnecessary.

Utilise the throttle for the desired sideslip

As discussed, the throttle input should be utilised for setting the target sideslip angle. This design corresponds to a typical RWD drifting vehicle without assist control, where applying throttle results in an increased slip ratio, causing the vehicle to drift deeper into corners with a higher sideslip. However, the distinction is that the throttle in our design does not directly manage the vehicle speed/slip ratio, the proposed concept assumes that once the drift control is enabled the controller will maintain the speed. As a result, we utilise a separate speed controller from CarMaker, and the throttle only contributes to the target sideslip β_d in drift mode, written as (4), where β_{d0} is the default sideslip angle (25 deg), γ is the throttle value from 0 to 1.

$$\beta_d = \beta_{d0} + 10\gamma \quad (4)$$

For real-world drifting where the throttle not only reflects driver's desired sideslip but also the speed command, a method is being developed in our future work to decouple the target sideslip and the desired speed from driver inputs, also to consider the relationship between speed and sideslip to satisfy the drift equilibrium.

Limit the sideslip rate

To ensure the driver has enough time to react and counter-steer to stay on track, we set the desired sideslip rate $\dot{\beta}_d$ as (5), where τ is a time constant and β is the current sideslip angle.

$$\dot{\beta}_d = \frac{1}{\tau}(\beta_d - \beta) \quad (5)$$

The path angle rate and yaw rate

After acquiring the sideslip rate $\dot{\beta}_d$, we proceed to analyse the vehicle's trajectory determined by the path angle rate $\dot{\phi}$, which is the sum of yaw rate r and sideslip rate $\dot{\beta}$, written as (6). At a steady cornering state where the road friction μ is nearly fully utilised, we assume $\dot{\phi}_d$ as (7) according to the track radius R . Hence, in order to maintain the trajectory radius while increasing the sideslip, the desired yaw rate r_d could be expressed as (8).

$$\dot{\phi} = r + \dot{\beta} \quad (6)$$

$$\dot{\phi}_d = \sqrt{\mu g/R} \quad (7)$$

$$r_d = \dot{\phi}_d - \dot{\beta} = \sqrt{\mu g/R} - \frac{1}{\tau}(\beta_d - \beta) \quad (8)$$

The yaw rate control and torque vectoring

To track the desired yaw rate in (8), we use the road friction μ and track radius R in (7) as predefined knowledge (a friction estimator and trajectory predictor will be proposed in our future work), and a torque vectoring controller is deployed with both feedforward and feedback components. The desired yaw moment M_z could be expressed as (9), in which k_{ff} , k_p , k_i are all coefficients.

$$M_z = k_{ff}I_z r_d + k_p(r_d - r) + k_i \int (r_d - r)dt \quad (9)$$

Subsequently, together with the overall longitudinal drive force $F_{x\text{sum}}$ decided by the speed controller, the longitudinal drive force for each side of the wheels could be expressed as (10), in which w represents the wheel track width of the vehicle.

$$\begin{aligned} F_{xl} &= 1/2F_{x\text{sum}} - M_z/w \\ F_{xr} &= 1/2F_{x\text{sum}} + M_z/w \end{aligned} \quad (10)$$

The next problem is to allocate F_{xl} , F_{xr} between the front and rear wheels respectively. Since in drifting the lateral force of front axle is near saturation and the rear wheels are fully saturated, to ensure that the rear axle saturates before the front, a coefficient c_f is introduced and determined based on the vertical load of the front axle F_{zf} , as shown in (11), in which F_z is the total load, and c_{f0} is an offset coefficient to guarantee that the rear wheels saturate prior to the front.

$$c_f = \frac{F_{zf}}{F_z} - c_{f0} \quad (11)$$

$$\begin{aligned} F_{xfl,fr} &= c_f(1/2F_{x\text{sum}} \mp M_z/w) \\ F_{xrl,rr} &= (1 - c_f)(1/2F_{x\text{sum}} \mp M_z/w) \end{aligned} \quad (12)$$

Furthermore, once the target longitudinal force F_{xi} has been determined, there is no wheel speed control implemented for slip ratio. Instead, similar to the work of Ref. [41], we assume that the drive torque is delivered as tyre force, as shown in (13).

$$T_{di} = F_{xi}r_w \quad (13)$$

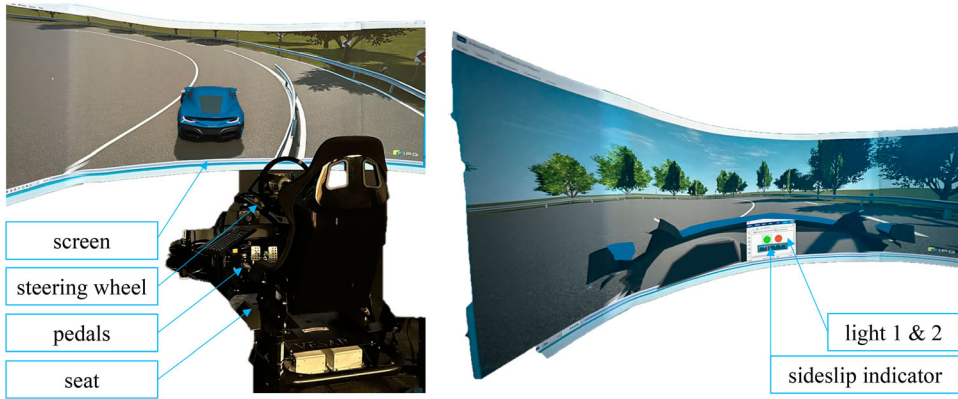


Figure 4. The hardware of the driving simulator.

The design of driver-in-loop trial on a driving simulator

To assess our abovementioned concepts of (1) limiting the sideslip rate and (2) using the throttle input for the desired sideslip angle, we utilise a driving simulator with recruited participants to drift on a circular track. And two tasks are designed for the above concepts: (1) Task 1 'Drift Trigger': in which the driver is expected to perform counter-steering intuitively to maintain the track while the sideslip is being increased at various rates by torque vectoring; (2) Task 2 'Increasing Sideslip with Throttle', in which the driver increases the sideslip by applying throttle, meanwhile cooperates steering with throttle for path tracking.

The hardware and software

The human trial was conducted using the driving simulator at Cranfield University, shown in Figure 4. The steering wheel is Leo Bodnar SimSteering, with a maximum torque of 16 Nm to produce realistic feedback. And the screen could provide a wide horizontal field of view of over 90 degrees. Note that the simulator is static in this paper but it is planned to add motion feedback in our further research. In addition, there are two lights and a sideslip indicator on the dashboard for the driver to effectively follow the trial procedures. As for the software configurations, the controller is built in Matlab/Simulink, while IPG CarMaker is utilised for vehicle dynamics simulation, as shown in Figure 5.

In addition, to evaluate the equilibrium analysis in the previous sections, and to validate the vehicle modelling inside CarMaker, drifting data from the simulation is presented in Figure 3 and shows a fair correlation (sideslip, slip ratios) with the analysis value, which supports both the equilibrium analysis and the driver-in-loop results in the following sections.

The participants

Approved by the ethics committee, 34 participants from Cranfield University have been recruited, and all of them have signed the informed consent form to allow us utilise the collected data. As for their background (Table 2), none of them claimed to be experienced

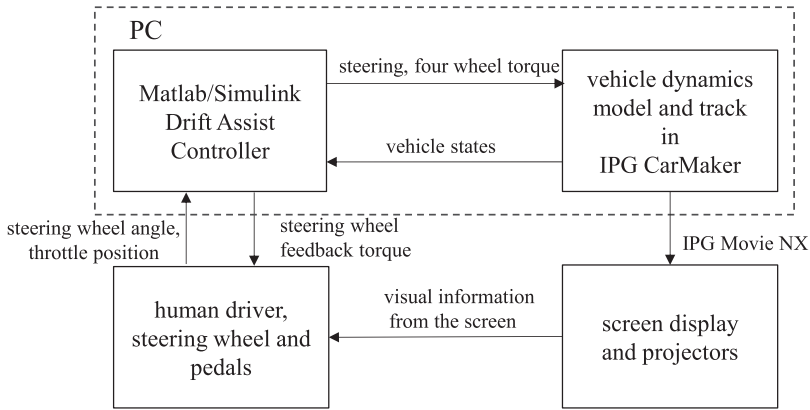


Figure 5. The software configuration of the driving simulator.

Table 2. Participants biography.

Participants bio	Min	Max	Mean	SD
Age (yrs)	21	31	24.4	2.8
Driving history (yrs.)	0	13	6.0	2.6
Experience in simulator	Yes		No	
Number of participants	17 (50%)		17 (50%)	

drift drivers, the mean value of their age is 24.4 years old ($SD = 2.8$), and the average driving history is 6.0 years ($SD = 2.6$).

The test procedure and variables

To validate our concepts of limiting the sideslip rate and using the throttle input for the desired sideslip, as shown in Table 3 and Figure 6, each run on the simulator is 100 s and involves two tasks to assess the two concepts respectively. During the initial 25 s, the driver does counter-clockwise normal cornering on a circular track with 20 m radius ($\mu = 1$), manipulating only the steering while the speed is controlled by a speed controller. Next, at 25 s the first light on the dashboard turns green indicating that full-throttle for 2 s is needed to activate the drift controller, consequently the sideslip angle starts increasing until it reaches the default -25 deg using torque vectoring. From 25 to 60 s, due to the increasing sideslip, the driver has to counter-steer quickly and precisely in order to stabilise the vehicle on track (Task 1). Subsequently, at 60 s the second light turns green, prompting the driver to apply throttle in order to increase the sideslip angle from -25 to -30 deg, simultaneously the driver must coordinate the steering in order to maintain the trajectory radius (Task 2) as discussed in Figure 3.

We further consider the effects of sideslip rate $\dot{\beta}_d$ (5) and the feedback torque applied to the steering wheel T_{sw} , which is determined based on the tyre self-aligning torque on the steering pinion T_{CM} in CarMaker. We expect that a lower sideslip rate (SR) requires less counter-steering rate as well as driving skills. And more steering torque feedback (TF) may demand more effort in steering, but provide more feedback of tyre force, as well as more

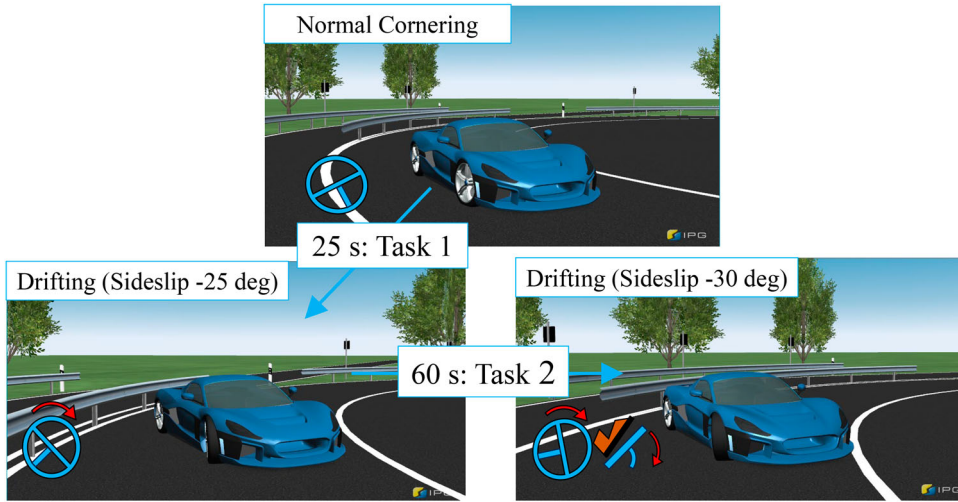


Figure 6. Procedures of driver-in-loop simulator trial.

Table 3. Procedures of driver-in-loop simulator trial.

Task	Time	Driver's action
/	0–25 s	Normal driving in circular track by steering (No need for throttle due to the speed controller)
Task 1: Drift Triggering	25 s (First light turns green)	Full throttle for 2 s to activate the drift controller with a target sideslip of -25 deg for torque vectoring.
(Throttle only works as drift trigger due to the presence of speed controller)	25–60 s	The driver has to perform counter-steer to stabilise the vehicle and maintain the track.
Task 2: Increasing Sideslip with Throttle	60 s (Second light turns green)	The driver is required to use the throttle in order to increase the sideslip to -30 deg.
(Throttle only contributes to target sideslip angle as (4))	60–100 s	Due to increased sideslip, the driver has to cooperate steering with throttle to maintain the trajectory radius.

Table 4. Variables of driver-in-loop simulator trial.

Variable	Equations	Level	Value of coefficient
Sideslip rate (SR)	$\dot{\beta}_d = \frac{1}{\tau}(\beta_d - \beta)$	Low (SR1)	$\tau = 0.5$ s
		Med (SR2)	$\tau = 1$ s
		High (SR3)	$\tau = 1.5$ s
Feedback torque on steering wheel (TF)	$T_{sw} = pT_{CM}$	Low (TF1)	$p = 50$
		Med (TF2)	$p = 100$
		High (TF3)	$p = 150$

aligning torque that prompts the driver towards counter-steering during drifting. For both variables, we set three different levels named as Low, Med and High as shown in Table 4.

With three levels for each variable, in total, we have nine different settings. With each setting run twice, each participant undergoes 18 runs. Importantly, prior to data collection, all participants are provided with a free practice to get familiar with the vehicle's dynamics,

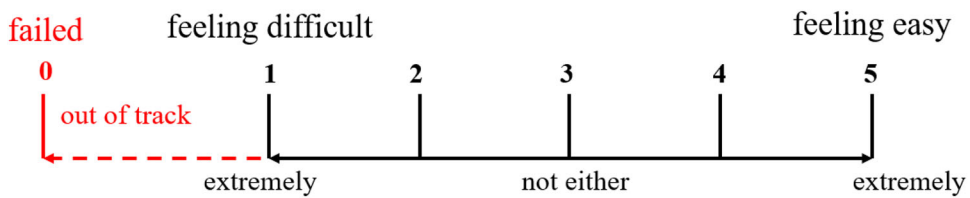


Figure 7. The subjective rating scales.

Table 5. Subjective evaluation results for Task 1: drift triggering.

Subjective rating/Failure rate	SR1	SR2	SR3	Mean
TF1	3.78 (2.9%)	3.19 (8.8%)	2.66 (5.9%)	3.21
TF2	3.96 (0.0%)	3.58 (4.4%)	2.90 (8.8%)	3.48
TF3	4.19 (0.0%)	3.55 (2.9%)	2.51 (10.3%)	3.42
Mean	3.98 (2.94%)	3.44 (16.2%)	2.69 (25.0%)	/

followed by another one to familiarise with the trial procedure. Most importantly, before the trial there is no tutorial to instruct the participants how to drift the vehicle, and the nine settings are run randomly, in order to evaluate the intuitiveness of our drift assist concept.

The design of subjective evaluation

After each run, the participant will be required to subjectively evaluate regarding two tasks. The first is for the transition from normal cornering to drifting (Task 1, 25–60 s), the participant will assess whether it feels easy to perform counter-steer and stabilise the vehicle after the drifting is triggered. The second focuses on the time period (Task 2, 60–100 s) using throttle to increase the sideslip, the participant will evaluate whether it feels easy to coordinate the steering with throttle in order to stay on track.

The rating scale ranges from 0 to 5, as illustrated in the Figure 7, with 1 indicating extreme difficulty and 5 representing the easiest. A rating of 0 is only assigned when the participant is unable to complete the task, either by running outside the track or spinning.

Results analysis for the driver-in-loop simulator trial

The analysis in this part will focus on the subjective and objective evaluation results regarding the two concerned tasks in Table 3. Specifically, the ratings and signals obtained from CarMaker will be utilised to discuss the driver's preference and performance.

Subjective evaluation

Task 1: drift triggering (counter-steering and transition from normal cornering to drifting)

In Task 1 the driver is expected to perform counter-steering intuitively to maintain the track while the sideslip is being increased by torque vectoring. The subjective evaluation results together with the failure rate of drift triggering are presented in Table 5.

In general, not only the rating itself but also the failure rate indicate that participants prefer the lowest sideslip rate (SR1), as the failure rate (where the driver spins or leaves the

Table 6. Subjective evaluation results for Task 2: increasing sideslip with throttle.

Subjective rating	SR1	SR2	SR3	Mean
TF1	3.82	3.52	3.35	3.56
TF2	4.01	3.82	3.63	3.82
TF3	4.34	4.12	3.46	3.97
Mean	4.06	3.82	3.48	/

track) is only 2.94% compared to 25.0% of SR3. This shows that drifting without assisted control could be very difficult, but lowering the SR can effectively reduce this difficulty. The reason is lower SR results in smoother yaw movement and allows the drivers for better preparation to counter-steer and keeps the vehicle on track.

Regarding the steering feedback torque, most participants have indicated that they receive more information about the force on the front axle when the steering torque feedback is at the 'heaviest' level (TF3). Interestingly, the lowest score does not result from the combination of TF1&SR3, but rather from TF3&SR3. In this scenario where the steering wheel is 'heavy' and the sideslip rate is high, one possible explanation is that the steering force is more abrupt, and the driver feel the vehicle uncontrollable when the drift control is activated.

Task 2: increasing sideslip with throttle (coordinate the steering with throttle)

In the second task, participants are instructed to use the throttle to increase the sideslip. Similar to the first one, as shown in Table 6, participants prefer a heavier steering wheel (TF3) and a lower sideslip rate (SR1). Additionally, participants find this task easier as indicated by generally higher scores compared to the previous task.

Objective evaluation

Task 1: drift triggering (counter-steering and transition from normal cornering to drifting)

The lateral deviation. For this task, the main concern is whether the driver can perform counter-steering quickly and correctly to maintain the target path. So, the first indicator to be analysed is the lateral deviation, the average (average of all the participants at each time step by interpolation, as the tasks are scheduled by time) and the interquartile range (IQR, 25th to 75th percentile) of which are shown in Figure 8.

The trend is clear that sideslip rate (SR) is the main factor affecting the average lateral deviation in Figure 8 (a). When the sideslip rate is at High level (SR3), the average curves in have more fluctuations than the other settings (maximum deviation > 2.8 m, Table 7), and when the sideslip rate is at Low level (SR1), the curves are almost flat with ignorable errors (maximum deviation < 1.5 m). Also, when there is more steering feedback (TF3), not only the mean error but also the spread of lateral deviation (IQR in Figure 8(b) is reduced compared to the results from lower steering torque feedback (TF1), regardless of different SR levels.

In addition, the above analysis has a good correlation with the subjective results. When the TF is higher and SR is lower, the participants not only subjectively feel better but also generate less tracking error.

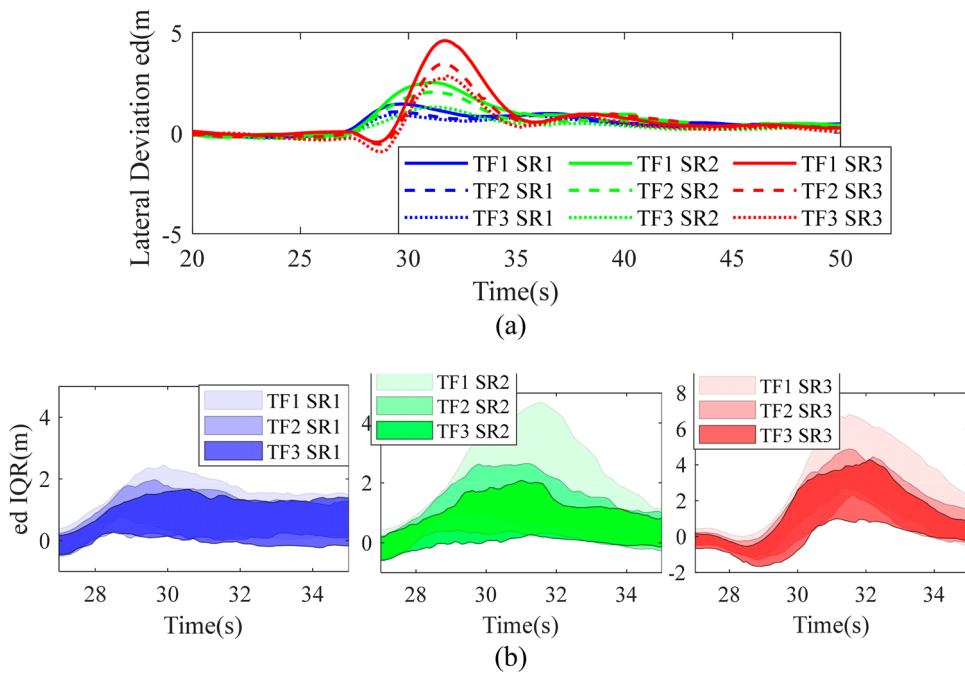


Figure 8. The average and spread of lateral deviation in Task 1: drift triggering.

Table 7. Maximum lateral deviation of Task 1: drift triggering.

Maximum deviation (m)	SR1	SR2	SR3
TF1	1.44	2.51	4.60
TF2	1.06	2.03	3.44
TF3	0.91	1.29	2.84

The steering wheel angle and the sideslip angle. The next step is to investigate the relationship between steering wheel angle (SWA) and sideslip angle (SA) during drift triggering, since both variables contribute to the trajectory radius (Figure 3), also because the steering affects the yaw moment while the drift controller destabilises the vehicle for target sideslip using torque vectoring.

As shown in Figure 9, firstly for SR2 and SR1 the sideslip curves are comparatively smooth, the sideslip is generated at different rates, and accordingly, the participants perform counter-steering at different speeds. A lower sideslip rate necessitates a lower counter-steering speed, resulting in more favourable subjective feedback.

However, for the high sideslip rate (SR3), there is a phenomenon that is worth further investigation. There are several fluctuations for both the SA and the SWA, which could be explained by considering the vehicle's lateral position. To be specific, SR1 and SR2 cases can be divided into three stages (marked as 1, 2, 3) during drift triggering: (1) Normal driving; (2) Drift triggered, a sideslip is generated shortly before the driver realise it and perform counter-steering, so the trajectory radius is slightly reduced and the vehicle deviates to the inner boundary; (3) The driver performs continuous counter-steering and stabilises

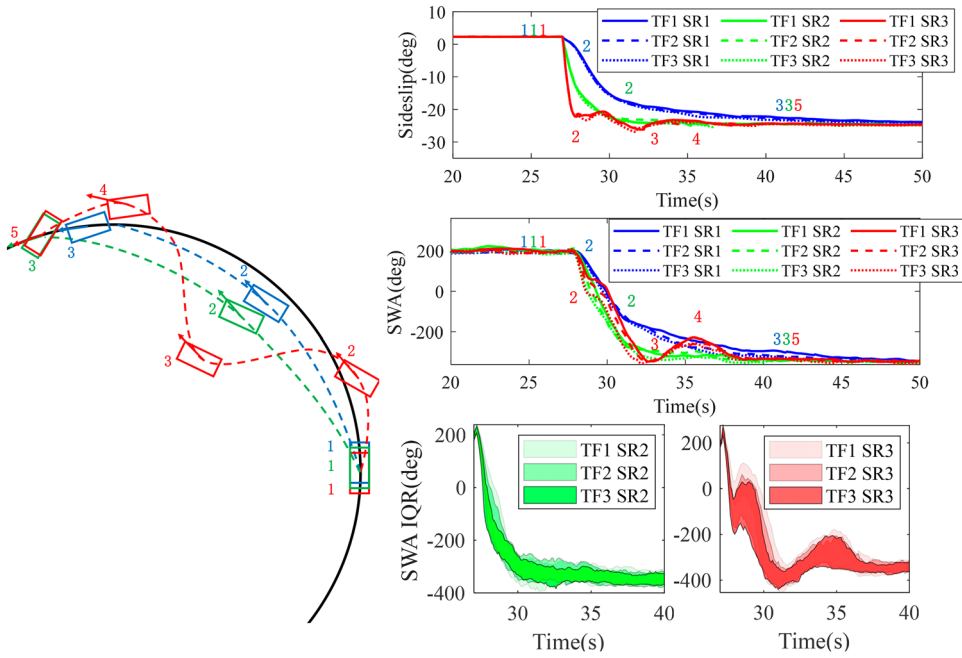


Figure 9. The trajectory, sideslip and steering angle of Task 1: drift triggering.

the vehicle back to track. In contrast, the SR3 case is divided into five stages: (1) Normal driving; (2) Due to the highest sideslip rate demand, to create more yaw moment the torque vectoring uses more longitudinal force and causes a significant reduction in the centripetal force, so the vehicle deviates to the outer boundary of the track (stage 2). And now the participants are facing a dilemma, even though they know they need more counter-steering due to sideslip, they have to reduce the counter-steering rate in order to bring the vehicle back to track. That's why the steering rate is reduced at stage 2 of SWA; (3) Once the vehicle gets back and moves towards the inner side (stage 3), the participants continue counter-steering (from stage 2 to 3 of SWA) not only to maintain sideslip but also to reduce the lateral deviation and move the vehicle back to the outer side; (4) Now the vehicle is moving from the inner (stage 3) to the outer side (stage 4), in order to follow the target path, the participants have to perform positive steering (stage 3–4 of SWA) to drive the vehicle back to track; (5) The driver performs continuous counter-steering and stabilises the drifting vehicle on track.

Besides, as for the effects of high TF, apart from reducing the spread of lateral deviation in the last subsection, it also slightly contributes to less spread of SWA particularly when SR is high (the IQR plot of SR2 and SR3 in Figure 9).

Task 2: increasing sideslip with throttle (coordinate the steering with throttle)

The throttle and the sideslip angle. In contrast to the previous task with a fixed target sideslip, in this task, the sideslip is controlled by the throttle, so the throttle and sideslip are analysed together in this section.

As shown in Figure 10, due to a limited sideslip rate, for SR1 the participants press the throttle deeper to over 60% in order to increase the sideslip angle faster. Nevertheless, the

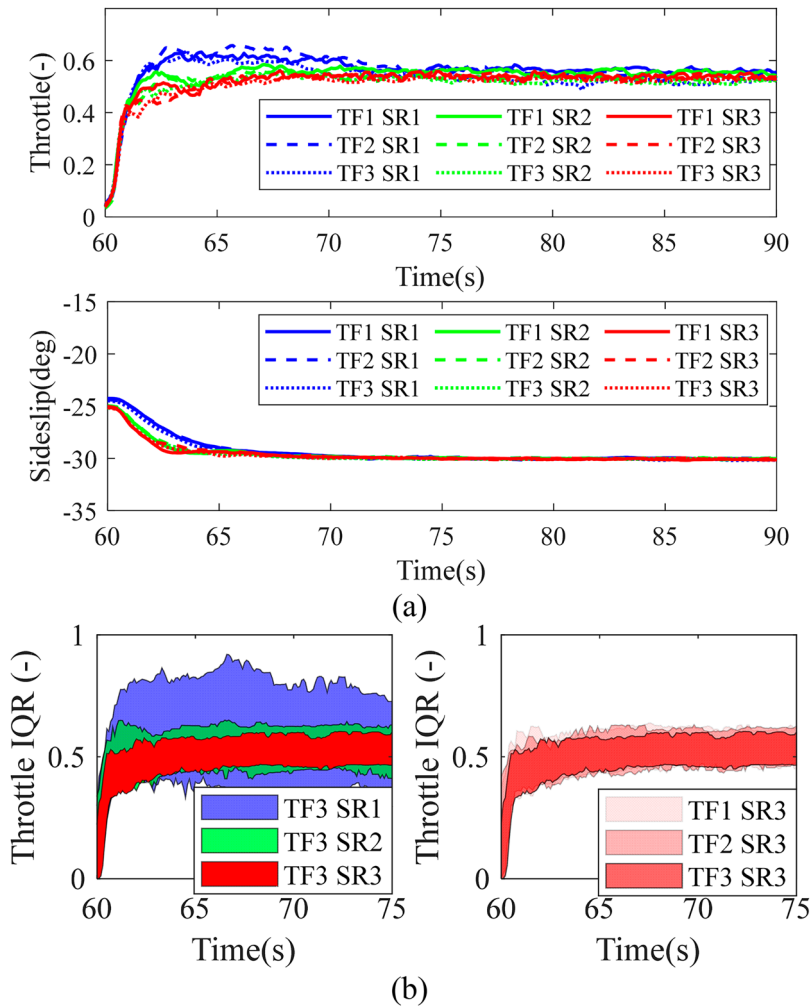


Figure 10. The average throttle and sideslip of Task 2: increasing sideslip with throttle.

sideslip still takes longer to converge to the target value (-30 deg) compared to the other two configurations.

To further assess the human effort in maintaining the sideslip through throttle control, it is essential to analyse the mean and standard deviation of throttle input, as presented in Tables 8 and 9. The patterns are evident: When the slip ratio is low (SR1), there is a noticeable delay in the sideslip angle response (Figure 10(a)), this not only prompts participants to apply more throttle (resulting in an increased mean value in Table 8), but also leads to a higher spread in Figure 10(b) left and standard deviation in Table 9.

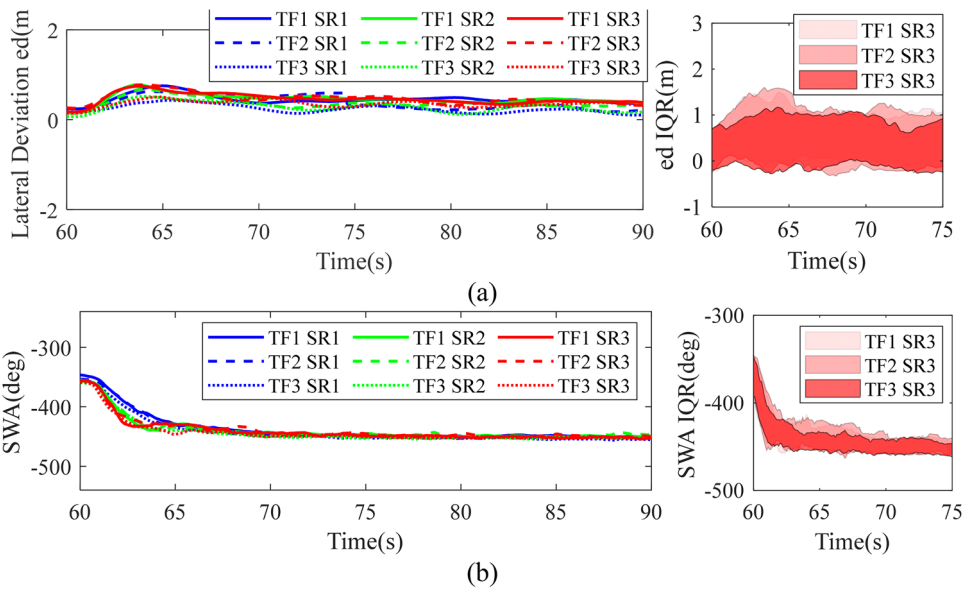
In terms of the impact of steering feedback torque, a higher TF value will result in a decrease in both the mean and standard deviation of throttle input (Tables 8 and 9, also in Figure 10(b) right). This can be attributed to the correlation between steering angle and sideslip angle at drifting equilibrium, that with fixed track radius, higher sideslip angle requires more counter-steering (Figure 3). And higher TF assists the driver applying the

Table 8. Mean value of throttle of Task 2: increasing sideslip with throttle.

Mean throttle (—)	SR1	SR2	SR3
TF1	0.282	0.244	0.239
TF2	0.264	0.240	0.237
TF3	0.252	0.239	0.231

Table 9. Standard deviation of throttle of Task 2: increasing sideslip with throttle.

Throttle SD (—)	SR1	SR2	SR3
TF1	0.372	0.312	0.298
TF2	0.345	0.302	0.295
TF3	0.340	0.298	0.289

**Figure 11.** The lateral deviation and steering wheel angle of Task 2: increasing sideslip with throttle.

correct amount of counter-steering, which in turn contributes to manipulation of throttle with less oscillation.

The steering angle and the lateral deviation. In the process of increasing throttle for more sideslip (Figure 10), participants must also apply additional counter-steer to keep the vehicle on track (Figure 3). Therefore, we evaluate the lateral deviation along with the steering, as shown in Figure 11.

In accordance to the participants' subjective feedback, where the task is judged to be relatively easy, the lateral deviation is almost negligible even at SR3 (the average and the spread are shown in Figure 11(a)), which means it is intuitive for the participants to counter-steer when the sideslip increases. To further investigate the impact of SR and TF on lateral deviation, the average lateral deviation under various settings is shown in Table 10. It is

Table 10. Mean lateral deviation of Task 2: increasing sideslip with throttle.

Mean deviation (m)	SR1	SR2	SR3
TF1	0.845	0.849	0.836
TF2	0.754	0.771	0.852
TF3	0.616	0.673	0.745

Table 11. Standard deviation of steering of Task 2: increasing sideslip with throttle.

Standard deviation (deg)	SR1	SR2	SR3
TF1	24.722	18.084	17.920
TF2	24.390	18.295	17.883
TF3	23.136	18.108	16.745

evident that TF plays a role, as the average lateral deviations of TF3 are smaller compared to the other settings. One possible explanation is that a higher TF assists the driver in counter-steering during the sideslip increase period (60–63 s), which contributes to trajectory tracking. However, the effects of SR are less clear particularly for TF1, as for TF2 & TF3 an increase in SR results in greater lateral deviation, possibly because higher sideslip response requires more skills in trajectory tracking.

To evaluate the steering effort of the driver, the standard deviation of steering angle is listed in Table 11. With higher SR, the sideslip and the yaw response are improved and, therefore, require less steering correction (standard deviation) for trajectory tracking. Meanwhile, higher TF offers more feedback about the front axle lateral force, making the steering task easier for participants and resulting in less correction as well (spread plot in Figure 11(b)).

Conclusions

In this paper, we present a concept of intuitive drift assist control for a 4WD electric vehicle that allows independent wheel torque control driven by an average driver and evaluate the concept through driver-in-loop trial using a driving simulator.

Firstly, by 4WD drift equilibrium analysis, we demonstrate the idea of incorporating throttle input besides the steering from the driver to decide the target sideslip angle, in order to decouple the steering effects on drift equilibrium states by using torque vectoring. To assist the driver in coordinating the steering with sideslip for desired trajectory radius, we propose to restrict the sideslip rate in order to provide the driver enough reaction time to counter-steer and stabilise the vehicle.

Subsequently, thanks to the over-actuated feature of 4WD vehicle with an independent motor for each wheel, we design a sideslip rate and yaw rate controller by using torque vectoring, without prior equilibrium information as reference.

To evaluate our control concepts, a circular track is built in the driving simulator using CarMaker and 34 participants are recruited to perform two tasks (Drift Triggering and Increasing Sideslip with Throttle) under nine different configurations of sideslip rate and feedback torque on steering wheel.

Finally, through subjective questionnaires and objective evaluation of vehicle motions, the results in general show that our concept can assist the driver in intuitively drifting the vehicle, particularly when the sideslip response rate is lower and the torque feedback on steering wheel is higher.

Future work

The drift assist control concept should be improved to consider varying trajectory radius and complex scenarios where the driver controls the speed. Additionally, the activation procedure should be developed to better interpret the driver's intention. The robustness of the system against disturbances is also critical considering we are operating beyond the limit of adhesion of the tyres, and will be explored in further work focusing on the control algorithm design.

Acknowledgement

The financial and intellectual contributions of Rimac Technology are acknowledged for their role in supporting this research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Evaluation of an intuitive 4WD drift assist control concept in a driving simulator

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2025-12-31

Taylor & Francis

<https://doi.org/10.1080/00423114.2025.2487186>

Sun Y, Velenis E, Krishnakumar A. (2025) Evaluation of an intuitive 4WD drift assist control concept in a driving simulator. Vehicle System Dynamics, Available online 10 April 2025