

Performance Enhancement of Road Vehicles Using Active Independent Front Steering (AIFS)

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ABSTRACT

Technological developments in road vehicles over the last two decades have received considerable attention towards pushing the safe performance limits to their ultimate levels. Towards this goal, Active Front Steering (AFS) and Direct Yaw-moment Control (DYC) systems have been widely investigated. AFS systems introduce corrective steering angles to conventional system in order to realize target handling response for a given speed and steering input. It is thus expected that such an action under severe maneuvers may cause one tire to reach saturation while the other tire may be capable of developing more force. This study, therefore, proposes an Active Independent Front Steering (AIFS) system capable of controlling a wheel independently. At low speeds, the proposed AIFS system will modify the steer angle with speeds while maintaining pro-ackerman geometry similar to an AFS system. In doing so, it will realize a target response defined as one provided by a neutral steer system. However, in a severe maneuver, as the inner tire approaches the saturation limit, the AIFS system controller will only increase the angle of the outer tire, effectively introducing an anti-ackerman geometry. The study is carried out using a comprehensive 4-wheel handling model with AIFS capability. A PI controller with ability to detect and control the outer wheel independently is incorporated to examine the handling performances of an understeer vehicle under a ramp-step and sinusoidal steering inputs. In general, the results demonstrate that AIFS can perform as well as AFS in realizing target response while AIFS can provide performance enhancement beyond the limits of AFS. The control approach of AIFS is also shown to be effective for split- μ condition.

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INTRODUCTION

The steering system design plays a vital role in determining the handling and stability performance of the road vehicles. During a directional maneuver, depending on the speed and nature of maneuver, the cornering force may be limited when one of the wheels approaches the adhesion limit before the others, which may affect the handling performance in an adverse manner. Active chassis controls such as anti-lock brake systems (ABS) and vehicle stability control (VSC) systems have thus drawn substantial efforts for enhancement of safety dynamic performance of road vehicles. Considerable efforts have been made towards steering- and yaw moment-based VSC systems such as active front steering (AFS) and direct yaw moment control (DYC) that are designed to meet the cornering demand for enhanced vehicle handling and stability performance [1,2].

The steering mechanism in conventional road vehicles is generally designed to closely follow the Ackerman steering ratio involving different steer angles of the inner and outer wheels at low speeds. At high speeds, the dynamics of a

vehicle and the side-slip angles developed at the tires cause the vehicle to follow a different path at different speeds for an identical steering input. This phenomenon due to the compliance of the pneumatic tire is known as understeer characteristic, which can be neutralized by actively controlling or modifying the steer angles of the steered wheels depending on the forward speed and the maneuver demands. This permits to enhance the lateral force developed by the tire to meet the cornering demands. Various concepts in active front steering (AFS) capable of providing continuous and situation-dependent variations in the steering ratio have thus been investigated to achieve improved low-speed maneuverability and high-speed stability performance. The concept of AFS was firstly introduced by Kasselmann and Keranen in 1969 [3]. Substantial further efforts have been made over the past two decades on different concepts and control strategies for the AFS system [4 and 5]. The AFS system, however, alters the steer angles of both the inner and the outer wheels simultaneously in order to realize a pre-determined target depending on the forward speed and

steering input, while the saturation limits associated with road adhesion are not considered. Owing to the nonlinear characteristics of pneumatic tires, a wheel may approach lateral force saturation under a high lateral acceleration maneuver and thereby limit its ability to generate the required lateral force. The AFS system may thus exhibit a very distinct limitation in providing the target response or controllability under high-g maneuvers that lead to significant lateral load shift between the inner and the outer wheels.

The yaw moment-based VSC systems (DYC), on the other hand, have been proven to be more effective than the AFS under high lateral acceleration maneuvers, since these generate the required yaw moment via differential braking [6 and 7]. A DYC system alone, however, yields limited performance in tracking a target vehicle response to steering inputs. Furthermore, it may cause a directional instability in an emergency braking maneuver on a split- μ condition, where the road adhesion limits of the left and right side could be substantially different. A number of studies have reported different limitations of the DYC systems, which include relatively longer stopping distance during emergency braking [8], reduced tire life due to more frequent braking, and over-ruled feeling of the driver by the additional corrective yaw moment [9]. Considering that the DYC and AFS systems could yield enhanced performance under different ranges of operating conditions, many studies have focused on coordinated control of AFS and DYC [10 and 11]. Although the integration of AFS and DYC systems has provided definite performance gains over a broad range of operating conditions, it results in a more complex control system involving various tracking or estimated parameters.

The performance potential of an AFS system could be considerably enhanced by introducing independent variations in the inner and outer wheels steering. This would permit the optimal utilization of the available adhesion of the both wheels to meet the cornering demand under high-acceleration maneuvers. Such a concept, referred to as Active Independent Front Steering (AIFS) system in this paper, would likely lead to enhanced handling and stability performance in the presence of split- μ conditions. Furthermore, the AIFS system can also be integrated with DYC for further enhancement of yaw stability performance since AIFS can also generate yaw moment by introducing differential lateral forces of the steered wheels. The implementation of AIFS, however, would necessitate the design of a practical mechanism capable of providing the desired steering ratio, which is perhaps one of the major challenges in realizing this concept. The reported studies on adaptive steering systems generally propose the use of "Steer by wire" [12 and 13], which has been widely investigated for the purpose of active front steering. The implementations of steer-by-wire technology in production cars, however, have been attempted together with a mechanical backup system. The mechanical active steering systems comprising a planetary gear system, harmonic drive system and variable ratio racks have been employed by BMW, Audi and Mercedes, respectively [14,15]. These are

generally designed with an objective to realize variable steering ratio (VSR), and thus aid the driver's steering effort by actively altering the steering ratio between the steering angle and the wheels' steer angles.

This paper investigates the concept of AIFS and a control strategy for a vehicle with an understeer characteristic to examine its effectiveness in enhancing the handling performance limit when compared to that realized by the AFS system. A control strategy is formulated and explored so as to utilize the maximum capability of both the steered wheels in order to augment the handling performance limit. For this purpose, the performance limit is defined as the maximum speed or curvature that can be negotiated in an adaptive manner to satisfy the ideal or target (yaw rate and trajectory) responses for a given road adhesion. A nonlinear handling model of a vehicle considering independent steering of the inner and outer wheels, and the lateral /longitudinal load shifts is employed to study the performance potentials of AIFS. The analyses are performed under ramp-step and sinusoidal steering inputs, and both uniform and split- μ conditions. A simple controller synthesis based upon PI control is applied to assess potential performance gains of the AIFS concept. Furthermore, since the concept of AIFS is based on load shift between the inner and outer wheels, this study also examines the sensitivity of the height of the center of gravity for the vehicle equipped with both AFS and AIFS systems. The simulation results demonstrate that AIFS performance is as good as those obtained by AFS system in non-critical handling maneuver. However, the effectiveness of AIFS in comparison to the AFS is significant when maneuvers performed are at the limits. A design concept of a mechanical fail-safe steering mechanism, reported in [16], is also explored for realizing the AIFS function.

HANDLING MODEL

A yaw-plane model of a road vehicle is formulated considering independent steering of the right- and the left-wheels to study the handling performance potentials of the AIFS system. The model, illustrated in Fig. 2, includes the longitudinal, lateral and yaw motions of the vehicle, nonlinear cornering properties of the tire and the load shift along the longitudinal axis. In the figure, δ_r and δ_l refer to two independent steering inputs to the right- and left-wheels, respectively. The relations between the steering wheel input (δ_{st}) and the right- and left-wheel angles, according to Ackerman geometry, can be expressed as:

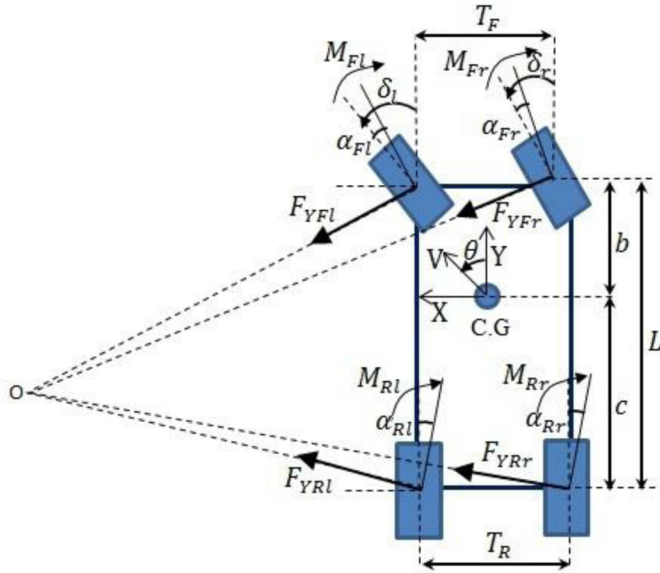


Figure 1. 3-DOF nonlinear handling model with independent steering angle.

$$\delta_r = \tan^{-1} \left[\frac{\sin(\delta_{st})}{\cos(\delta_{st}) + \frac{T_F * \sin(\delta_{st})}{L}} \right] \quad (1)$$

$$\delta_l = \tan^{-1} \left[\frac{\sin(\delta_{st})}{\cos(\delta_{st}) - \frac{T_F * \sin(\delta_{st})}{L}} \right] \quad (2)$$

Where T_F and T_R are half tire track width of the front and rear axle, respectively, L is the wheelbase and δ_{st} refers steering command of the driver reflected at the wheels considering parallel steering. The studies reporting handling models generally consider lateral force normal to the fore-aft tire axis as opposed to the direction of travel, assuming considerably lower side-slip angles compared to the steer angles [17]. The tires may undergo substantial side-slip during severe handling maneuvers, which would not only alter the effective yaw moment but also the coordinates of the instantaneous center of rotation. It is thus important to consider side-slip angles in deriving the effective forces and the yaw moment. The equations of longitudinal, lateral and yaw motions of the vehicle model, derived in the absence of braking or acceleration force, are given below:

$$ma_x = -F_{YFr} \sin(\delta_r - \alpha_{Fr}) - F_{YFl} \sin(\delta_l - \alpha_{Fl}) + F_{YRr} \sin(\alpha_{Rr}) + F_{YRl} \sin(\alpha_{Rl}) \quad (3)$$

$$ma_y = F_{YFr} \cos(\delta_r - \alpha_{Fr}) + F_{YFl} \cos(\delta_l - \alpha_{Fl}) + F_{YRr} \cos(\alpha_{Rr}) + F_{YRl} \cos(\alpha_{Rl}) \quad (4)$$

$$I_{zz} \dot{\Omega} = - \sum_{i=F}^R \sum_{j=r}^l M_{ij} + F_{YFr} \{ b \cos(\delta_r - \alpha_{Fr}) - T_F \sin(\delta_r - \alpha_{Fr}) \} + F_{YFl} \{ b \cos(\delta_l - \alpha_{Fl}) + T_F \sin(\delta_l - \alpha_{Fl}) \} + F_{YRr} \{ -c \cos(\alpha_{Rr}) + T_R \sin(\alpha_{Rr}) \} - F_{YRl} \{ c \cos(\alpha_{Rl}) + T_R \sin(\alpha_{Rl}) \} \quad (5)$$

In the above equations α_{Fj} and α_{Rj} are the slip angles of tires on the front and rear axles, where the second subscript ($j = r, l$) refers to right- and left -wheels, respectively. For a given forward velocity, the path trajectory of the vehicle in the global coordinate system is obtained from the instantaneous yaw angle of the vehicle, such that:

$$X = \int_0^t V \cos \theta dt, \quad Y = \int_0^t V \sin \theta dt \quad (6)$$

Where V and θ are the vehicle speed and the yaw angle of the vehicle, respectively.

TIRE FORCE AND MOMENT

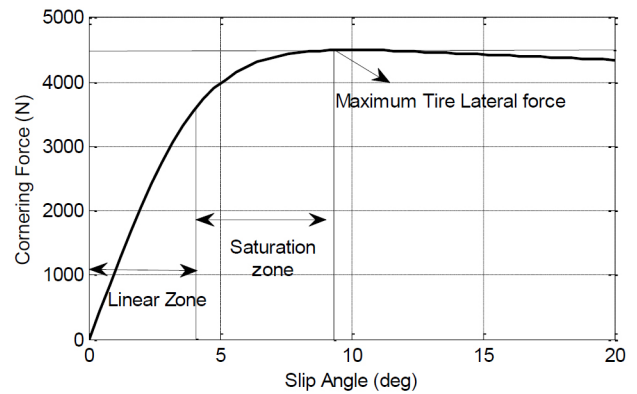


Figure 2. Tire lateral force zones.

In this study, the “Magic Formula” tire model [18] has been utilized to derive lateral force F_{Yij} ($i = F, R; j = r, l$) developed at the tire-road interface and the aligning moment, where subscripts F and R refer to front and rear tires, and r and l denote the right and left wheels, respectively. The tire lateral force can be characterized in two distinct ranges of side-slip angles, as it is evident in the cornering force properties of tires shown in Fig. 2. The tire force generally lies in the nearly linear region under typical vehicle maneuvers. Under extreme maneuvers or slippery road conditions, the tire force occurs in the nonlinear or the saturation region, which is vital in this study considering that one of the requirements for the proposed AIFS system is to prevent the tire from approaching the saturation. As shown in the figure, the changes in the tire lateral force and

consequently the yaw rate with change in the steering angle tend to diminish at the end of the saturation zone.

Tire normal load is the other major factor that influences the cornering behavior of the tires. In a severe turning maneuver, the normal load shift between the outer and inner wheels plays a greater role. Furthermore, the relation between the normal load and the lateral force is nonlinear, which leads to a reduction in the total cornering force developed during a turning maneuver and greater side-slip angle in order to meet the lateral force demand [18]. Neglecting the load shift attributed to vehicle roll in the context of the yaw plane model considered in the study, the normal loads on each wheel F_{Zij} ($i=F, R; j=r, l$) can be expressed as functions of the longitudinal (a_x) and lateral (a_y) accelerations in the following manner:

$$F_{ZFr} = \frac{W_F}{2} - \frac{ma_x h_{cg}}{2L} + \frac{ma_y h_{cg} c}{2T_F L} \quad (7)$$

$$F_{ZFl} = \frac{W_F}{2} - \frac{ma_x h_{cg}}{2L} - \frac{ma_y h_{cg} c}{2T_F L} \quad (8)$$

$$F_{ZRr} = \frac{W_R}{2} + \frac{ma_x h_{cg}}{2L} + \frac{ma_y h_{cg} b}{2T_R L} \quad (9)$$

$$F_{ZRl} = \frac{W_R}{2} + \frac{ma_x h_{cg}}{2L} - \frac{ma_y h_{cg} b}{2T_R L} \quad (10)$$

The side-slip angles of the tires are expressed as functions of the forward and lateral velocity and yaw rate of the vehicle, as follows:

$$\alpha_{Fr} = \delta_r - \tan^{-1} \left[\frac{b\Omega + V_y}{V_x + T_F \Omega} \right] \quad (11)$$

$$\alpha_{Fl} = \delta_l - \tan^{-1} \left[\frac{b\Omega + V_y}{V_x - T_F \Omega} \right] \quad (12)$$

$$\alpha_{Rr} = \tan^{-1} \left[\frac{c\Omega - V_y}{V_x - T_R \Omega} \right] \quad (13)$$

$$\alpha_{Rl} = \tan^{-1} \left[\frac{c\Omega - V_y}{V_x + T_R \Omega} \right] \quad (14)$$

The tire lateral force and self aligning moment are subsequently obtained from the Magic Formula Tire model [20] as functions of the tire normal force and slip angle:

$$Y(X) = D \sin \{ C \tan^{-1} [B X - E (B X - \tan^{-1} (B X))] \} \quad (15)$$

Where $Y(X)$ presents the cornering force or the self-aligning moment, X is tire slip angle; C is the shape factor and B, D and E are coefficients dependent upon the normal load.

AIFS CONTROL STRATEGY

A control strategy for AIFS is synthesized considering the two distinct regions of the tire cornering properties. Under relatively low lateral acceleration maneuvers, the tire is expected to operate in its linear range. The steering control strategy in this region is identical to that of the AFS system, where a corrective angle is applied equally to both the front wheels in order to track the desired yaw rate target. In this case, the wheels approximately follow the Ackerman geometry, where $\delta_l > \delta_r$ for the left turn maneuver illustrated in Fig. 1. Greater load transfer and centrifugal force encountered during a high lateral acceleration maneuver, however, could cause saturation of the inner wheel, while the available adhesion of the outer wheel being under-utilized, as illustrated by points 'A' and 'B' in Fig. 3. This tendency would limit the performance of the AFS controller as one of the wheels approach or exceed the saturation regime.

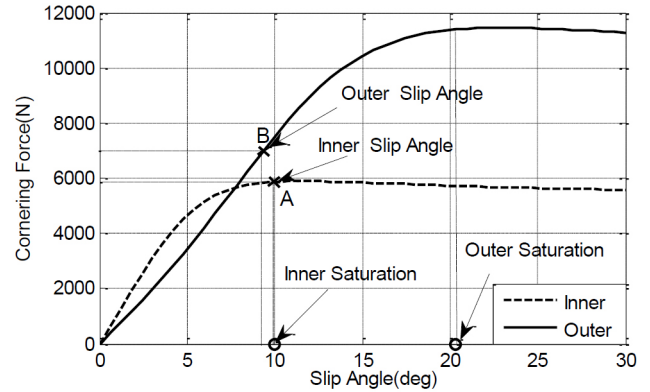


Figure 3. Inner and the outer tire lateral force in a turning maneuver.

Subsequently, the AIFS controller is synthesized to ensure maximum utilization of the available adhesion limits of both the wheels in a high lateral acceleration maneuver. Unlike the AFS controller, the proposed control strategy considers independent steering corrections applied to the right- and left-wheels, which can be realized through design of an independent steering system. The proposed design, presented in the subsequent sections, permits distribution of the corrective action between the inner and the outer wheels with different gains depending upon the operating conditions namely the speed, road adhesion and instantaneous steering wheel angle. For an understeer vehicle, the controller thus results in relatively greater steering of the outer wheel than the inner wheel so as to utilize the available adhesion limit of the outer wheel more efficiently, while limiting the inner wheel to operate slightly below its saturation limit. In this case, depending on the maneuver, the outer wheel steer angle