

# A Model-Free Stability Control Design Scheme with Active Steering Actuator Sets

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## ABSTRACT

This paper presents the application of a proposed fuzzy inference system as part of a stability control design scheme implemented with active steering actuator sets. The fuzzy inference system is used to detect the level of oversteer/understeer at the high level and a speed-adaptive activation module determines whether an active front steering, active rear steering, or active 4 wheel steering is suited to improve vehicle handling stability. The resulting model-free system is capable of minimizing the amount of model calibration during the vehicle stability control development process as well as improving vehicle performance and stability over a wide range of vehicle and road conditions. A simulation study will be presented that evaluates the proposed scheme and compares the effectiveness of active front steer (AFS) and active rear steer (ARS) in enhancing the vehicle performance. Both time and frequency domain results are presented.

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## INTRODUCTION

The recent introduction of electric power steering (EPS) and steer by wire systems has opened the way for the introduction of many active vehicle control functionalities. For example, Orozco [1] showed that by actively controlling the front wheel angle, it is possible to increase driver comfort by counter-acting side wind force disturbances. Along the same lines, Ackermann [2] uses a reference yaw rate to determine the driver's intention and activate the active steering system with the intention to reduce the driver's mental work load. Sano et al. [3] showed that by using a feed forward A4WS to apply an in-phase steer angle at the front and rear wheels, it is possible to reduce the vehicle phase lag during a lane change test without compromising lateral acceleration. This led to better driver control performance and enhanced stability. Sano et al further proposed a passive rear wheel steer angle control that is proportional to the front wheel steer angle and can set the steady state side-slip angle to zero [4]. They also describe a feed-forward plus feedback algorithm for active 4 wheel steer (A4WS) that can keep the body side-slip angle close to zero. In [5], the yaw rate signal is used to generate a feedback loop to the rear wheels for compensating external disturbances. Hadare used optimal controls theory to show the potential improvements that an A4WS system can achieve in closed loop [6].

However, these advances in technology are not used in current systems. Production Vehicle Stability Control systems (VSCs) heavily rely on linearized vehicle models and table-based threshold adjustments in the main control scheme. These model-based approaches rely on parameters like vehicle mass and nominal tire

cornering stiffness's. Those parameters are subject to change during the vehicle's life cycle. More importantly, a VSC system is most critical in limit handling situations where the tires exhibit non-linear behavior and cornering stiffness-based models do not hold. Furthermore, road force or slip angle estimators, which have difficulties adapting to fast changes in road conditions, cause errors in the model. Even though many research works exist that try to compensate the model simplifications and uncertainty with different adaptive or robust control proposals that often carry a large on-line computational complexity, the reliance of the designs at least on a nominal model is the key hurdle. This issue is particularly important in the development process involving various prototypes/phases. The engineer calibrates the active steering and stability control system once for the first prototype phase and then has to retest and retune for every change to the vehicle, tire, and steering system.

In this paper, an active steering stability control system is described that is integrated into a proposed model-free VSC design scheme. The latter is, developed in our companion work [7], where a fuzzy-inference system (FIS) is trained to detect behavioral deviations from a neutral steer vehicle and generates an understeer (US) or oversteer (OS) indicator. Based on the detected OS/US indicator, which is computed at the high level of the VSC, an active four-wheel steering (A4WS) actuator set will be activated to bring the vehicle back to a neutral steer behavior. The complete VSC system is calibrated once using training data and is robust enough to control the vehicle under a multitude of load and road conditions without further changes. The model-free VSC is developed in Matlab/Simulink® and

co-simulated with two CarSim® vehicle models. The vehicle models represent two different types of vehicles, 1) an SUV, and 2) a Sedan. The performance of the model-free VSC is evaluated in a standardized ECE R13H Sine with Dwell simulation [8] and frequency domain evaluations.

## MODEL-FREE VSC ARCHITECTURE WITH A4WS

The structure of the model-free VSC is shown in Figure 1. Conceptually, the implementation is organized in 4 stages. The detection stage uses vehicle signal inputs, like longitudinal vehicle speed ( $V_x$ ), lateral acceleration ( $A_y$ ), yaw rate ( $Av_z$ ), and road wheel angle (RWA), to detect and categorize unstable vehicle behavior as oversteer or understeer. This is done in a single fuzzy inference system (FIS). The output is one final indicator that categorizes the unstable situation on a scale of -10 for heavy oversteer to +10 for heavy understeer. The activation stage uses the stability indicator from the detection stage and combines it with vehicle signals to decide which axle to steer (only front wheel steer (AFS), only rear wheel steer (ARS) or a combination (A4WS)). The calculation stage is responsible for computing the actual wheel angles necessary to stabilize the vehicle. Finally, the application stage combines the calculated wheel angles with a vehicle-speed adaptation parameter and sends the signal to the vehicle's steering actuators.

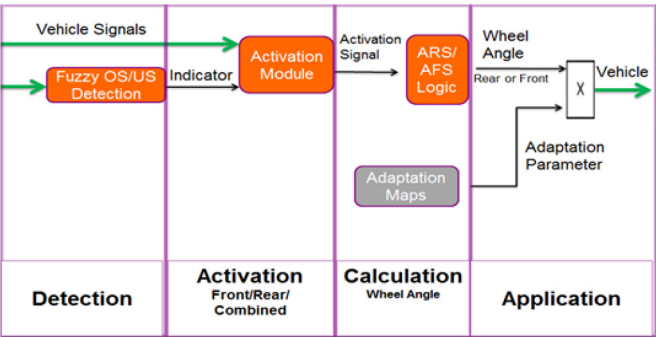


Figure 1. A4WS VSC Architecture

The following subsections explain the four VSC stages in further detail.

### 1. Detection Stage - Fuzzy OS/US Indicator

The detection stage constantly monitors the five vehicle signals: steering wheel angle (SWA), steering wheel rate (SWRATE), yaw rate (AVZ), yaw acceleration (AAZ), and lateral jerk (AAY) and feeds them to the fuzzy OS/US detection module. The model-free fuzzy inference system (FIS) uses the incoming signals to determine the current state of the vehicle. It categorizes that state in one OS/US indicator on a scale from -10 for heavy oversteer to +10 for heavy understeer. The reader is referred to our companion paper [7] for details on the design of this FIS.

### 2. Activation Stage

Once oversteer or understeer is detected, the activation module is responsible for deciding which steering actuator set (AFS, ARS, or both A4WS) is best suited to improve vehicle stability and handling. Comparisons between the effectiveness of active front steer (AFS) and active rear steer (ARS) during either OS or US maneuvers have shown that not all unstable situations can be optimally handled with utilization of ARS or AFS. During understeer, ARS seems to be most promising. The reasons for this are explained in the A4WS effectiveness analysis in the simulation results section. Therefore, US events should be controlled with ARS. OS maneuvers should be controlled with AFS as long as this is sufficient. If this is not the case anymore, ARS and AFS are combined to stabilize the vehicle. Figure 2 shows an overview of the activation scheme.

The activation module is responsible for choosing the right mode for the situation at hand and for activating the front wheel angle or the rear wheel angle calculation stages/blocks. The workings of the module are illustrated with Figure 3. It consists of an Activation m-file and switches for each of the front wheels and the rear wheels. The m-file takes the OS/US indicator and the steering wheel angle as input. It uses the OS/US Indicator to evaluate the situation, categorize the required response in one of the 4 modes and sends the mode/activation number to the switches (see Figure 3). Then, the switch outputs are sent to the ARS and AFS logic in the calculation stage to activate them if necessary.

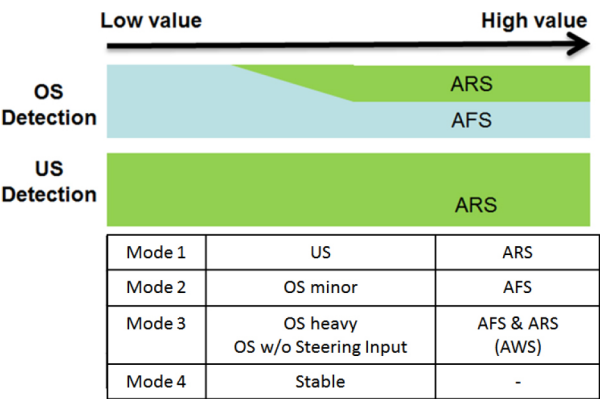


Figure 2. Activation Module Schedule and Modes

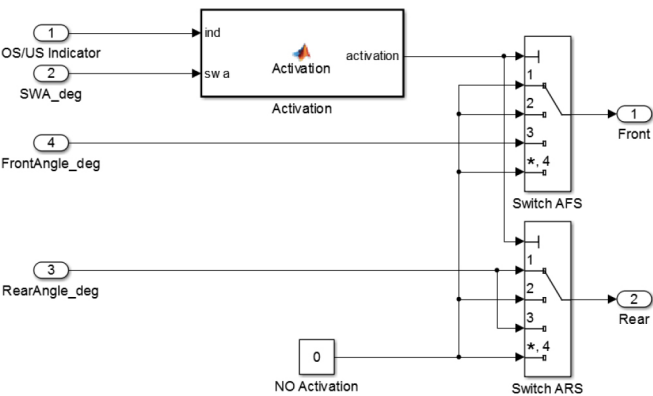


Figure 3. Simulink Model of Activation Module

### 3. Calculation Stage

After the unstable vehicle behavior is detected and the decision is made on whether ARS, AFS, or a combination of both is more effective in stabilizing the vehicle, the actual wheel angles necessary to improve the vehicle behavior must be calculated. This is done in the calculation stage within the calculation module. This module consists of 3 parts as displayed in Figure 4.

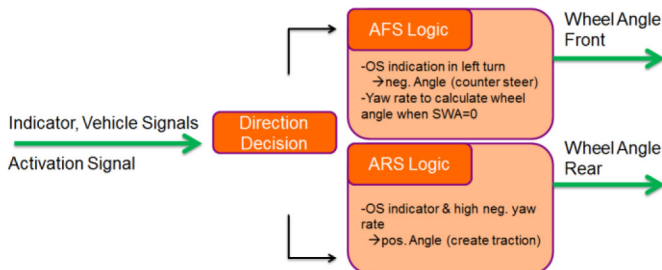


Figure 4. Calculation Module (OS)

Suppose an understeer event is detected. So far we know that the OS/US indicator is going to be negative in this case, therefore the activation mode is going to be 1 for an activation of the ARS. In this case, the ARS calculation logic will set a rear wheel angle that is out of phase (opposite) to the front wheels to increase the yaw rate. The calculation module uses the steering wheel angle as an input and calculates the appropriate rear wheel steering direction to achieve out-of-phase steer. The ARS logic increases the amount of corrective steer with increasing understeer severity, represented by the OS/US indicator.

In case of an oversteer event, the main priority is to reduce the tire slip angle in the rear. In this case the wheels are turned toward the direction of the yaw rate, which will reduce the slip in the rear and stabilize the vehicle. This reaction can cause in-phase steer, which is often used in the literature for ARS oversteer control themes, but it does not necessarily have to be in-phase. The idea behind this is to decouple the front wheel angle from the rear wheel angle. This way both front and rear tire slip can be optimally controlled. Another advantage of using the yaw rate for ARS control instead of the steering angle is that the vehicle can be stabilized even when the driver counter steers or the steering wheel angle becomes zero.

The AFS logic always counter-steers during oversteer with a wheel angle that is out-of-phase with the (driver) steering wheel angle. Again, increasing OS indication results in increasing steering effort. In case of a steering wheel angle that is zero, the AFS direction decision is based on the yaw rate, similar to the ARS.

### 4. Application Stage

In the application stage, the calculated wheel angles from the calculation stage are adjusted and applied to the vehicle. The final adjustment is necessary to adapt to different operating vehicle speeds. Low speed understeer maneuvers require relatively high rear wheel angles to reduce understeer. If the same angles are applied to the wheels in high vehicle speeds, the US control would cause excessive yaw rate and to uncontrollable oversteer. It is therefore necessary to adapt the calculated wheel angles according to the vehicle speed. The adaptation parameters were identified using a series of simulations

with different vehicle speeds, road conditions, and maneuvers. Figure 5 shows the resulting parameters for different activation scenarios. These values multiply the calculated wheel angle before it is applied to the vehicle.

With increasing speed, the magnitude of understeer control is reduced, in order to prevent excessive yaw rate, while the oversteer control is increased. It is important to mention that the oversteer control AFS adaptation has a maximum at 100 km/h and is reduced after that. The reason for this is in the nature of the AFS control. It reduces the front wheel angle and counter steers. High AFS control can reduce the front wheel angle so much that the vehicle is unable to stay on the desired path. A tradeoff between stability and desired trajectory has to be made under these conditions.

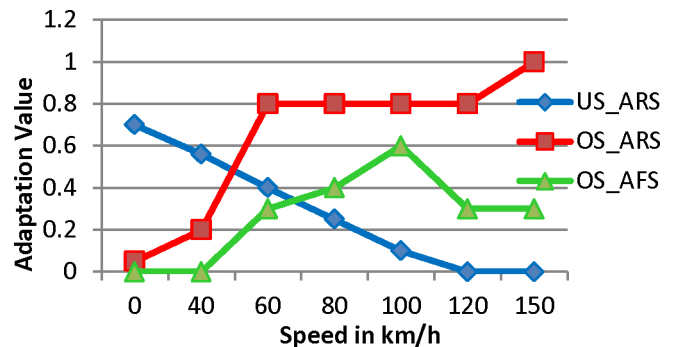


Figure 5. Adaptation Parameter

Finally, the adapted wheel angles are applied to the vehicle. It is worth mentioning that these corrective wheel angles are merely added to the steering input of the driver. For example, a driver input causing of a front wheel angle of 10 degrees and a corrective AFS front wheel angle of -2 degrees results in an effective front wheel angle of 8 degrees, not including compliance steer effects.

## SIMULATION RESULTS

The purpose of the test procedures is first and foremost to evaluate the performance of the model-free VSC control using active steering actuator sets. However, a secondary objective is to evaluate the effectiveness of ARS as compared to AFS in controlling certain unstable situations like OS or US. For the purposes of this study, the procedures are selected to be open-loop. This way any contributions and uncertainties of the driver models effectiveness in stabilizing/destabilizing the vehicle or in competing with the VSC can be excluded. Furthermore, the tests must represent maneuvers typically used for VSC system evaluations. The selected open-loop test procedures are briefly discussed in the following subsections.

### Sine with Dwell

Sine with Dwell (SwD) is a typical maneuver specified in regulations for VSC evaluation such as the ECE R13H [8]. For the purpose of evaluating the VSC's performance under different conditions including heavy unstable vehicle behaviors, we deviate from the definition in the regulations. The sine with dwell procedure is simulated for multiple, constant vehicle speeds, and constant road conditions, as well as with relatively high steering wheel angles to

determine the VSC performance under limit handling conditions.

Figure 6 shows the open-loop steering input of the SwD maneuver as well as the evaluation parameters. The yaw rate at point 2 as well as the maximum lateral vehicle displacement at point 3 due to the steering input are desired to be as high as possible, indicating good understeer control. The yaw rate at point 4 as well as the time and magnitude of the yaw rate overshoot after the steering input should be as small as possible, indicating proper oversteer control and stability.

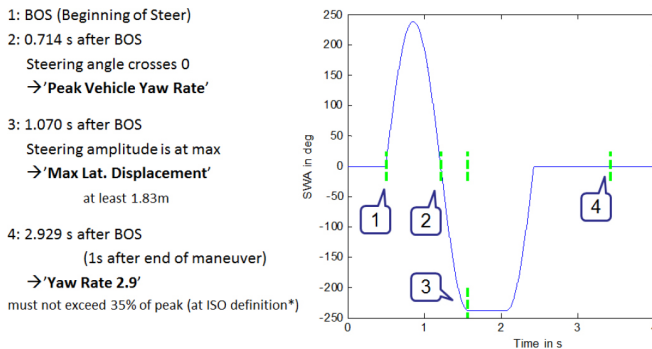


Figure 6. Sine with Dwell Steering Input (right), Evaluation Parameters (left)

### Frequency Response

A sinusoidal driver steering input with constant amplitude and quadratically increasing frequency is used to generate the frequency responses. For different tests, the amplitude is adjusted to achieve certain lateral acceleration values from 0.3g up to 0.5g staying within the linear tire range. Then, five response parameters, proposed by Linke [9], are used to determine the performance. These parameters are represented in a spider plot as shown in Figure 7. The axes are directed so that better results cause more area under the spider plot.

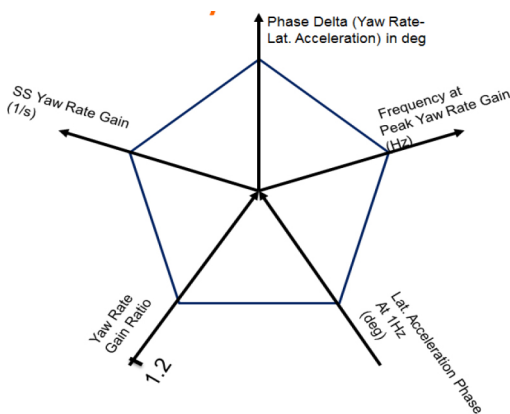


Figure 7. Frequency Response Evaluation Parameters

### ACTIVATION STAGE - A4WS EFFECTIVENESS ANALYSIS (UNDERSTEER)

In this section, we take a closer look into the effectiveness of ARS compared to AFS in improving understeer. We define understeer in terms of yaw rate as a deficiency in building up the driver's requested

yaw rate. This is shown as a difference in actual yaw rate compared to a driver request yaw rate that we define as the yaw rate a neutral steering vehicle would provide. Another qualitative measure for understeer is the magnitude of the front wheel slip angle compared to the rear wheel slip angle. A larger magnitude of front slip angle compared to rear slip angle indicates understeer. Again, this is simply a qualitative measure, unlike the yaw rate. There are several factors contributing to the slip angle of a wheel, like drive torque and tire specifications. Therefore we will only use this parameter qualitatively.

The main reason for an understeer control is to improve the trajectory by increasing the yaw rate. The most important indicator for the comparison between ARS and AFS will therefore be the ability to raise the yaw rate. In order to determine this, an array of sine with dwell tests maneuvers for various vehicle speeds was simulated. For each vehicle speed the maximum steering wheel angle of the SwD steering input and the adaptation parameter of the VSC application stage was changed to see the effect on the creation of yaw rate at the evaluation point 2 in the SwD maneuver. Figure 8 shows one of these results. The simulations use a constant vehicle speed and road friction. For each maximum steering wheel angle (amplitude of sine wave input) the vehicle is simulated first only with AFS intervention for understeer control (red surface). Following the line of a constant steering angle, for example 60 degrees, the first simulation (front right data point 1 in Figure 8) uses an US adaptation parameter of -1.5. This means that the VSC logic output angle is scaled by -1.5 and then applied to the front wheels, resulting in a reduction of front wheel road angle. The resulting vehicle yaw rate is plotted on the vertical axis. Following the line of 60deg maximum steering wheel angle to the left, we can see the resulting vehicle yaw rate for an US adaptation parameter of +1.5, resulting in an increasing front wheel angle.

The green surface illustrates the resulting vehicle yaw rate using a VSC control with only ARS intervention. The adaptation parameters are only positive and not negative, since only out of phase application of rear wheel angle can create increasing yaw rates for ARS. Figure 8 shows that the ARS control is superior at increasing vehicle yaw rate over the AFS control under any steering wheel angle, for low vehicle speeds (40km/h) on low friction surfaces. Figure 9 shows the same test for a higher vehicle speed. A multitude of these tests for various vehicle speeds and maximum steering wheel angles are conducted. The results show a clear trend. At vehicle speeds below 60km/h, the ARS control is superior in creating yaw rate over the AFS control (Figure 8). At higher vehicle speeds, the AFS control can raise the yaw rate significantly as long as the steering angle of the maneuver is relatively low, therefore leaving the front tires far in their linear range. By increasing the front wheel angle under these specific circumstances (Figure 9 front left corner) the vehicle yaw rate can be raised. As soon as the level of steering input by the driver increases this advantage over the ARS is lost. The dependency on the front wheel slip angle (max steering angle) makes it difficult to implement AFS in the US control logic. Future work will investigate the feasibility of a more nonlinear US control logic in the activation stage.