Driver Response to Active Front Steer and Power-Assist Failures

Hamish Jamson*, Phil Wiffin† and Peter Burchill†

*Institute for Transport Studies, University of Leeds, LS2 9JT.

†Jaguar Research

Abstract

Active Front Steer (AFS) has the ability to apply varying road wheel angles for the same steering wheel angle, depending on the speed of the vehicle. It achieves this by changing the steering gain dynamically and can be a useful driver aid: less steering wheel input is required at low speeds than a more traditional fixed-gain steering system to achieve the same radius of turn. Should an AFS system fail, it is designed to revert back to a fixed-gain system. Concerns have been expressed by designers of AFS systems that this sudden change in steering gain may prove hazardous for drivers and be particularly difficult for them to handle.

The present study had three main aims:

- To compare drivers' behaviour using both fully-functioning AFS and power-assisted, fixed-gain, rack-and-pinion steering systems.
- To compare driver behaviour and response to the failures of both AFS and to the power-assist of a fixed-gain, rack-and-pinion steering system.
- To conclude whether failure of AFS is potentially more hazardous than failure of the power-assist of fixed ratio, rack-and-pinion steering systems.

Using the fixed-base Leeds Driving Simulator, this study compared driver behaviour using both AFS and fixed-gain steering systems. Failures of each system were also investigated. Fixed-gain system failure was simulated by a loss of steering power-assist. Forty drivers, balanced for age and gender took part in the study.

Results showed that fully-functioning AFS had some advantages over fully-functioning fixed-gain steering. Drivers found AFS less demanding, demonstrated by the fact that they showed significantly fewer steering reversals. They also rated AFS as easier to control in curved sections. Whilst making left-hand turns at a series of T-shaped intersections, there was a highly significant worsening of driver performance between steering functioning normally and failed steering. However, drivers found AFS failure no harder to manage than power-assist failure. Indeed, there were statistical trends suggesting that, if anything, AFS failure was easier for drivers to deal with than loss of power-assist.

Introduction

The function of a steering system of a vehicle is to steer the front wheels in response to driver commands in order to provide effective direction control. The large majority of the current vehicle fleet uses a simple rack-and-pinion steering system, where driver rotational inputs to the steering wheel are transformed by the pinion to a translational motion of the steering rack. The steering rack is connected to the steering arm by a tie-rod, the connection controlling the steering angle proportional to the rack movement.

AFS is a system pioneered by BMW (Köhn et al., 2002; Krenn and Richter, 2004) and is currently available as an option for the first time on the new BMW 5 series. The system is made up of a rack-and-pinion steering system, a double planetary gear and an electrical actuator motor. By adjusting the steering gain (rack travel versus steering input), the system has the ability to modify the driver-demanded road wheel angle at the input to the steering rack, depending on the speed of the vehicle.

AFS can be a useful driver aid: less steering wheel input is required at low speeds than a more traditional fixed-gain steering system to achieve the same radius of turn. Should an AFS system fail, it is designed to revert back to a fixed-gain system. Concerns have been expressed by designers of AFS systems that this sudden change in steering gain may prove hazardous for drivers and be particularly difficult for them to handle.

By observing driver behaviour in the Leeds Driving Simulator, the present study, funded by Jaguar Cars, had three main aims:

- To compare drivers' behaviour using both fully-functioning AFS and power-assisted, fixed-gain, rack-and-pinion steering systems.
- To compare driver behaviour and response to the failures of both AFS and to the power-assist of a fixed-gain, rack-and-pinion steering system.
- To conclude whether failure of AFS is potentially more hazardous than failure of the power-assist of fixed ratio, rack-and-pinion steering systems.

Methodology

Participants

40 drivers took part in the study. Experienced simulator drivers were recruited with a stipulation that they had at least two years driving experience and drove at least 4000 miles per annum. The sample was balanced for gender and age (under 35 and over 35) giving four groups: young male, young female, old male, old female. The demographics of the groups are show in Table 1 along with their means and standard deviations (SD). Drivers were paid for their participation in the study.

Driver group	Age	Driving experience	Annual mileage
Young male	28.1 years, SD = 3.3	9.4 years, SD = 3.9	12800 miles, SD = 10623
Young female	27.1 years, SD = 4.0	9.2 years, SD = 4.3	8800 miles, SD = 5094
Old male	53.5 years, SD = 14.7	33.6 years, SD = 13.6	11400 miles, SD = 7575
Old female	55.4 years, SD = 17.5	27.1 years, SD = 14.1	8350 miles, SD = 4056

Table 1: demographics of the participant driving sample

Driving Simulator

The study was performed using scenarios created in the Leeds Driving Simulator (Figure 1). The simulator is currently a fixed-based facility, built around a complete Rover 216GTi with its driver controls and dashboard instrumentation fully operational. The projection system consists of five forward channels, the images edge-blended to provide a near seamless horizontal field of view of 230°. A rear view (60°) is back projected onto a screen behind the car to provide an image seen through the vehicle's rear view mirror. The frame rate is fixed to a constant 60Hz.

The simulation uses naturalistic scenery modelled using MultiGen-Paradigm Creator and operates with in-house code to model realistic vehicle dynamics and intelligent scenario control to choreograph specific traffic events. Although the simulator is fixed-base, torque feedback at the steering wheel is provided via a motor fixed at the end of the steering column and a vacuum motor provides the brake pedal booster assistance. Data are collected at the frame rate.

Figure 1: The Leeds Driving Simulator

Experimental design

There were two main experimental factors under investigation:

- steering type (AFS, power-assisted fixed-gain)
- steering failure (steering functioning normally, steering failed)

The study was designed as within-subjects, such that each driver experienced both types of steering system, both functioning normally and under failure. Steering failures occurred at give-way intersections where drivers were required to make a left-hand turn.

Steering type

The two steering types were modelled in the simulator. The AFS system was simulated according to Burchill (2003), allowing a variable steering gain over a speed range from rest to 100mph (Figure 2). The power-assisted, rack-and-pinion system had a fixed steering gain of 40mm/rev, equating to a steering ratio of steering wheel to road wheel movement of around 18:1.

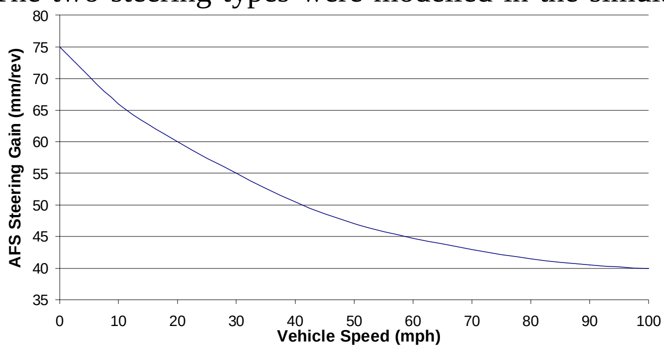


Figure 2: change in AFS steering gain with vehicle speed

Steering failure

For the AFS system, the variable steering gain that was apparent before failure was fixed at 40mm/rev after failure. Power-assistance to the steering was still available. The effect to the driver, particularly at low speed, was that larger than expected steering wheel input was required in order to negotiate a turn of fixed radius. For the fixed-gain system, failure constituted of a loss of power-assist. The effect to the driver was that the expected steering angle was still required, but much larger effort was required to rotate the steering wheel in order to achieve a fixed radius turn.

Virtual road network

Participant drivers drove the same experimental road network three times. The road network was about 8km long with a 96kph (60mph) posted speed limit and took around 8 minutes to complete. There were two 3.65m wide lanes, one in each direction with no verge nor shoulder to the lane. There were three T-shaped intersections in the road network and drivers were given automated auditory instructions to turn left at each of these junctions. The surrounding virtual environment mimicked a rural road layout with medium density, on-coming traffic. Participant drivers were instructed to drive as naturally as possible, bearing in mind the speed limit of the rural road.

Experimental procedure

Data collection took around one hour per driver. Participants drove the simulator five times during their visit. Firstly, they drove a practice road network in whichever condition of steering type they had first been allocated. The order in which steering type was experienced was counterbalanced, such that half of the drivers participated with AFS first followed by fixed-gain steering and half with fixed-gain followed by AFS. During the first practice session, driver re-familiarised themselves with the handling of the simulator over around 10km of winding, virtual road at around 50-60mph driving speed. They also practised negotiation of ninety-degree, left-hand turns at number of T-shaped intersections; at least six practice manoeuvres were performed.

After practicing at both low and high speeds with a given steering type, data collection began during the second drive. The three T-shaped intersections of the experimental road network (

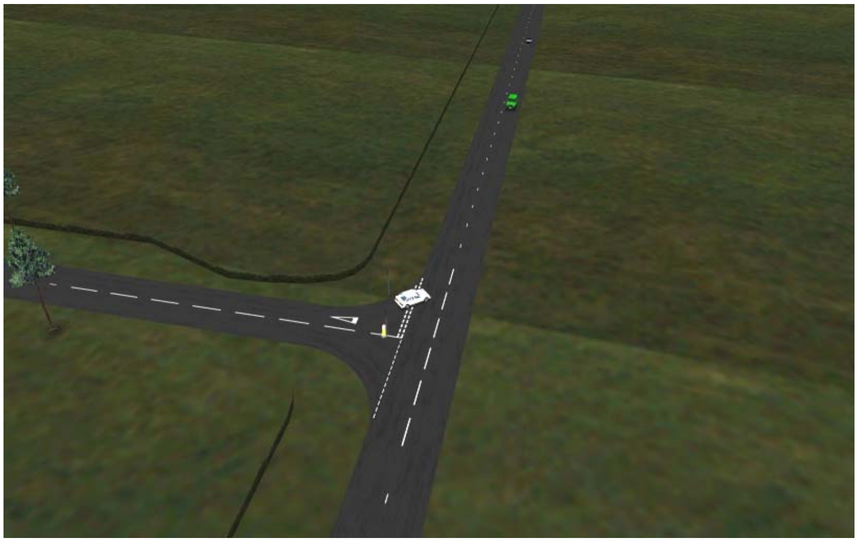


Figure 3) were each separated by around 2km. The separating sections were both *straight* and *curved*. A *straight* section was 864m in length (30s of driving at 60mph). A *curved* section of roadway, also 864m, was made up of 18 curved segments making a double s-shaped bend. Curves varied left and right, radius fluctuated between 510m and 750m. This gentle curving scenario required some negotiation by the driver and workload was considered to be higher than the simple straight sections.

Figure 3: intersection negotiation and on-coming vehicles

During this second drive, the vehicle's steering performed normally up until the third and final junction. When the vehicle was 30m away from this intersection, the steering "failed". The experimental run concluded when the intersection had been negotiated and the vehicle was at least 100m along the next road segment. Oncoming vehicles at the intersections motivated drivers to return to an accurate lane position as soon as possible (

Figure 3).

For the third drive, steering type was changed from either AFS to fixed-gain or vice versa. This drive was another familiarisation drive, exactly the same as the first drive, except with the alternate steering type. Again, at least six 'practice' intersection negotiations were performed.

Data collection for the alternate steering type was made during the fourth drive. This was identical to the second drive, except that there were no steering failures. This was because it was felt that after the second drive, participants may have begun to associate the third intersection with a steering failure. In order to minimise these learning effects and to keep each steering failure as unexpected as possible, the failure of the alternate steering type occurred on the fifth and final drive, during the first intersection encountered.

Results

With fully-functioning steering, repeated-measures ANOVA were used. The two within-subject factors were scenario (two levels: straight and curved section) and steering type (two levels: AFS and fixed gain (FG) steering). Normality and sphericity tests performed to ensure that the assumptions of ANOVA were not violated. For the analysis of steering failures, only the intersection scenarios were used since failures only occurred at these locations. Again, repeated-measures ANOVA were used but since the two steering types were quite different in their respective failure mode, a single within-subject factor design was employed: *steering condition* (AFS, fixed gain (FG), AFS fail, power-assist fail).

Driver self-reported ratings

Ratings were made on how easy the participants found the control of the vehicle with its current steering system. Participants were required to rate the steering system on a scale from 0 to 10 (low score = difficulty to control).

Fully-functioning steering

The mean of all ratings made for straight and curved section for both steering types are shown in Figure 4. There was a main effect of scenario in that steering in curves was rated as more difficult than in straights, $F(1,39)=27.9$, $p<.001$. There was no effect of steering type ($F(1,39) = 0.46$, $p=.50$) but the interaction almost reached significance, $F(1,39)=3.43$, $p=.072$. This interaction suggests that FG was rated much lower than AFS on curves than on straights.

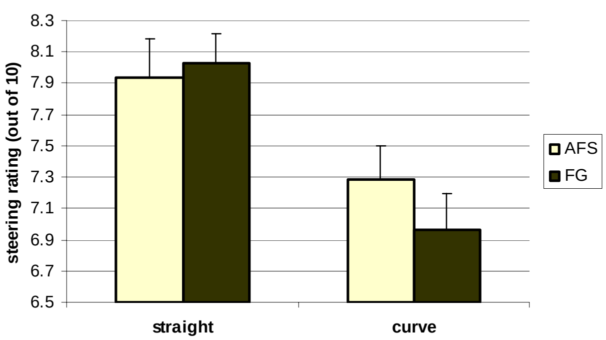
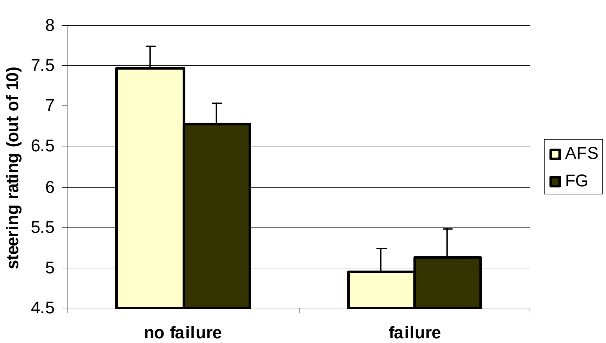


Figure 4: steering rating for AFS and fixed gain steering (FG) on straight and curved sections

Steering failure

A comparison of ratings was also made at intersections with both types of steering type both functioning normally and failed (Figure 5). There was a main effect of steering failure with drivers rating failed steering much lower than fully-functioning steering, $F(1,39)=57.2$,



p<.001. There was no effect of steering type (F(1,39) = 1.37, p=.25) but the interaction again almost reached significance, F(1,39)=3.49, p=.069. Considering the no failure condition alone, AFS was rated higher than FG, but this effect did not quite reach significance, F(1,39)=3.60, p=.065.

Figure 5: steering rating for normally functioning and failed AFS and FG at intersections

Steering reversal rate

The number of 1° steering reversals per minute (McLean & Hoffmann, 1975), steering reversal rate, was recorded over each curve and straight section. Mean values are shown in Figure 6. As with previous measures of lateral performance, the number of steering reversals was significantly lower on straights and than curves, F(1,39)=165, p<.001. There was also a main effect of steering type, in that there were significantly higher reversal rates with drivers using the fixed gain steering as opposed to AFS, F(1,39)=5.15, p=.029. There was no interaction between scenario and steering type, F(1,39)=.07, p=.79.

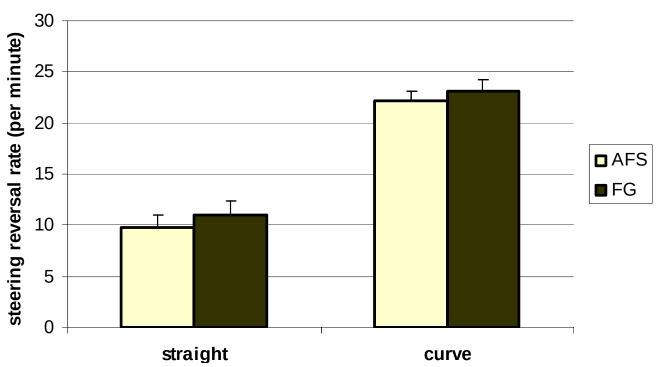


Figure 6: steering reversal rate for AFS and FG on straight and curved sections

Time spent out of lane

As the lane position achieved by the outside of each offside wheel was recorded during intersection negotiation, it was also possible to measure the time spent with any part of the vehicle outside of its lane boundary, including an inferred lane boundary during intersection negotiation. The red hatched area of Figure 7 shows the inferred lane boundary. Time spent out of this area during intersection negotiation was defined as time spent out of lane.

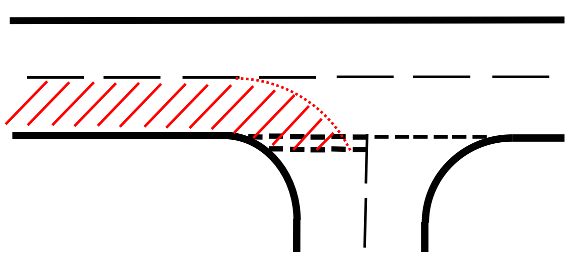
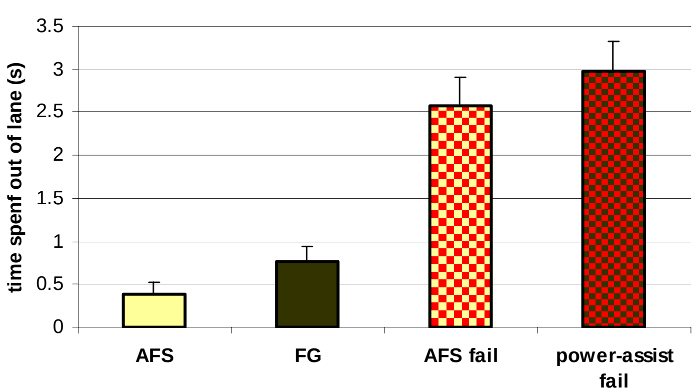


Figure 7: intersection inferred lane boundary (denoted by red hatched area)



There was a strong main effect of steering condition, F(3,117)=34.2, p<.001. Post-hoc tests (Tukey LSD) showed that in both failed states, drivers spent longer periods whilst encroaching into the adjacent lane than with steering functioning normally (AFS-AFS fail, $p<.001$; AFS-power assist failure, $p<.001$; FG-AFS fail, $p<.001$; FG-power assist fail, $p<.001$). There was a trend suggesting that in fully-functioning steering conditions, drivers encroached for shorter durations with AFS than with FG ($p=.095$) and also with AFS failed compared to assistance failure ($p=.15$).

Figure 8: time spent out of lane during/after intersection for all steering conditions

Discussion

This investigation examined the effects of and differences between an Active Front Steer (AFS) and a power-assisted, fixed-gain steering system on driver behaviour. In order to assess the effects of each individual steering system, behaviour was recorded with systems functioning normally on straight and curved sections of roadway. Drivers also encountered several T-shaped intersections both with functioning and failed steering to evaluate the severity of such failures. The study took place using the Leeds Driving Simulator.

At first, drivers experienced fully-operational steering systems on a single-carriageway, rural road with a posted speed limit of 60mph. Driver had to negotiate both straight and curved sections of virtual road. On average, drivers rated AFS higher, in that they found it easier to position their vehicle in lane with this system as opposed to fixed-gain steering. However, this was a trend only on curved sections of road; there was statistically no difference in ratings on straight sections. This result is probably not too surprising as straight sections, in general, require less driver interaction in order to negotiate effectively. This ‘easy’ driving has probably been shown as a floor effect in driver ratings. Since negotiating a straight is more straight-forward than negotiating a curve, the subtle difference between steering systems is potentially lost. Since they rated AFS higher on curves, drivers were likely to feel more confident with that system. This may be the reason that they tended to drive slightly quicker with AFS. However, this result was not statistically significant and thus no compensatory effect (increased speed due to less demanding steering controls) was proven. This is promising as no vehicle designer would want to loose a safety benefit (increased speed) to gain a safety benefit (less demanding steering).

Lateral control measures tended to back up drivers’ reported preference of AFS. Drivers had significantly fewer steering reversals, suggesting less mental effort was required in maintaining accurate steering. Drivers also showed significantly less variation in steering wheel movement. Partially due to a system effect (AFS at these speeds requires around 11% less steering input from the driver), less steering wheel variation is also associated with a less demanding steering task. Whilst the type of steering system had little effect of variation in lane position, the more sensitive measure of time to line crossing also showed trends towards a safety benefit of AFS, particularly on curved sections of road.

Whilst these fully-functioning steering results are interesting, the main aim of the study was to assess the severity of AFS failure compared with failure in the power-assist of the fixed-gain steering system. All of the driving measures employed during intersection negotiation were recorded between the *start* and *end* of intersection negotiation. *Start* was defined as the time at which the centre of gravity of the vehicle crossed the dashed give-way line of the junction. *End* occurred when the driver managed to 'straighten up' the vehicle, characterised as achieving a heading error of less than 1° for at least 2s and was the initial time frame of this 2s period. Whilst drivers took significantly longer to regain control of the vehicle (*end* time – *start* time) with a steering failure than with the corresponding steering functioning normally, there was no observed difference between the two full-functioning steering conditions (AFS and fixed-gain) nor between failed steering conditions (AFS failure and power-assist failure).

As drivers always made a left-hand turn at intersections, a lane boundary could be inferred during the left-turn and then again when joining the main traffic stream (Figure 7). Between the *start* and *end* of intersection negotiation, the maximum lane position achieved, i.e. the largest distance from the offside of the vehicle to the lane boundary, was much greater during a steering failure than with steering fully-operational. However, as in the case of time to regain control, there was no established difference for drivers experiencing AFS failure and when they underwent a failure of power-assist. However, in terms of time spent out of the inferred lane boundary, drivers tended to encroach into the adjacent lane for longer periods with fixed-gain steering than with AFS. This may due to the fact that there is a lesser steering wheel input requirement with AFS. Drivers also tended to encroach marginally further during power-assist failure than during AFS failure.

Conclusions

In summary, some advantages of fully functioning AFS over fully-functioning fixed-gain steering were demonstrated. Drivers found the steering less demanding (fewer steering reversals) and rated AFS easier to control in curved sections. Whilst all of the driving measures employed during intersection negotiation showed a worsening of driver performance between steering functioning normally and failed steering, it appeared that it was no harder for drivers to manage AFS failure than power-assist failure. In fact, there were statistical trends suggesting that, if anything, AFS failure was less disturbing than power-assist failure.

References

Burchill, P. (2003). Simple X202 Steering Model: Production Version. Internal Jaguar Report.

Köhn, P., Baumgarten, G., Richter, T., Schuster, M. and Fleck, M. (2002). The Active Steering System: the New Dynamic Road Handling and Steering System from BMW. 11th Aachen vehicle and engine technology colloquium, Aachen, 2002.

Krenn, M. and Richter, T. (2004). Active steering – BMW's approach to modern steering technology. In: Barton, D.C. and Blackwood, A (Eds.): Braking 2004. Vehicle Braking and Chassis Control. pp 3-14.

McLean, J.R. and Hoffmann, E.R. (1975). Steering reversals as a measure of driver performance and steering task difficulty. Human Factors, 17, 248-256.