Driver Steering Override Strategies for Steering based Active Safety Systems

Diomidis Katzourakis, Claes Olsson, Nenad Lazic
1Volvo Car Corporation (VCC)
2Chalmers University of Technology

ABSTRACT: The decreasing cost of sensory technologies including camera and radar has facilitated the outspread of advanced driver assistance (ADAS) systems into modern vehicles. ADAS systems can operate beyond the scope of stability control, by employing autonomous intervention in both longitudinal and lateral direction. Adaptive cruise control and lane-keeping aid (LKA) are the pinnacles of ADAS technology and have proven to reduce both driving effort and unintended lane-drifts. The current paper compares Volvo’s current and a concept driver steering override strategy applicable to LKA systems. The driver steering override theme evaluates the driver’s interaction with the vehicle and modulates accordingly the level of intervention. Both strategies quantify the driver’s activation by means of steering torque and road/vehicle information. Three different scenarios of lane drifting have been simulated; the results show that the override strategy has a decisive influence on the LKA benefits, depicting therefore the need for careful design and rigorous testing.

KEY WORDS: driver override, lane-keeping aid, path control, safety benefit, steering feel

1. INTRODUCTION

The electronic stability control (ESC) system, compares the driver’s intentions with the vehicle’s actual response, and compensates for any undesired effect by automatically braking individual wheel and possibly steering (active front steering). Studies since 1998 have showed the ESC’s effectiveness (1), suggesting that ESC could reduce skidding accidents up to 80% (2). ESC must first detect a problem before a corrective action can be taken, while, ADAS systems consider the driver’s intended path and share the vehicle control with the driver, “operating under the principle that the driver should be aware of the system’s activity by force information on the control interface” (3).

LKA systems estimate the vehicle’s position relative to the road using a camera to track road markings; they can interact with the driver, to prevent an unintended lane departure, using from audible, visual, to haptic steering-wheel feedback. Nowadays, many high-end automobile manufacturers (e.g., Volvo, Mercedes, Audi, BMW, Nissan-Infiniti and Honda) offer LKA systems in their top-class models for its undisputed benefits. Lane departure appears relevant to 179,000 crashes per year and related up to 7,500 fatal crashes per year in U.S. (4), and is usually induced by the driver’s inattention, distraction or impairment. Nissan started to offer a lane-keeping support system (5) in 2001 (Nissan Cima, (6)). Toyota (7) in 2002 and Honda (8) in 2003 launched their lane-keeping assist systems that apply steering-wheel torque to help drivers to keep the vehicle in the lane.

Nissan (Infiniti) was the first to offer lane-departure prevention (LDP) using the brakes to keep the vehicle on the appropriate lane (9). A global installation of LDP could result in 12% reduction annual of road fatalities according to Infiniti (10). The majority of Infiniti vehicles owners in the study of Braitman et al. (9), equipped with lane-departure warning (LDW) and LDP reported that they “disliked nothing” about the systems and stated that they drifted from the lane less often. Similarly, the U.S. Dept. of Transportation (11) studied the effects of a lateral drift warning system and showed that drivers improved their lane-keeping, spent 63% less time outside the lane, and increased their use of turn signals.

Mulder et al. (12) showed the efficiency of continuous haptic support in curve negotiation with the driver and system to share steering control; Della Penna et al. (13) applied the same principle with positive results in obstacle avoidance situation. Although human-centred automation, with the driver always in control of the vehicle, receiving solely feedback through the steering-wheel has received quite attention (3)(12)(13)(14), the required level of automation is still under discussion. Human limitations in speed and decision-making might suggest that a high level of automation may be preferable in certain cases (15)(16)(17). Studies on adaptive cruise control (ACC) (18)(19) suggest that automation has its pitfalls; despite the fact that ACC is acknowledged to reduce mental workload, it has also been blamed to provoke false reliance on the system (19). Drivers with miscomprehension of the ACC functionality could have an increased collision risk (16), due to disengagement from their driving task, and increased response time (18). A study from Katzourakis et al. showed that drivers may fail to understand the functionality of a LKA system leading to inadvertent driver reactions (20). Driver compatibility with the human can therefore be the most challenging part in the design of LKA systems (21).
In this paper, two different steering override strategies are described and compared with respect to their impact on override effectiveness, path control performance, as well as the expected benefit of active safety systems. The two strategies have been evaluated in the Volvo Car Traffic Simulator (VCTS) in Matlab/Simulink. Three different lane-drift scenarios have been devised to enable the comparison between the two strategies. The results presented in the corresponding section, show that the override strategy has a decisive influence on the LKA performance, depicting therefore the need for careful design and rigorous testing.

2. PROBLEM STATEMENT

The driver’s intention to take over the control of the vehicle in the middle of a steering intervention is termed as driver steering override. The earlier an intervention is triggered in a specific traffic scenario, the lower is the criticality of the traffic situation and the more demanding are the requirements on the override strategy. This is due to the number of unwanted interventions which are likely to increase. Hence, for an intervention corresponding to a highly critical and accordingly non-frequent traffic situation, a less sensitive override strategy should be adopted. However, to allow full automatic steering intervention, adoption of redundancy schemes would be required. This case is out of the scope of this work.

In previous work on autonomous steering, a scheme is sometimes proposed where either the driver or the autonomous system steers the vehicle (22). Such a strategy is desirable from a steering feel perspective but at the same time, assuming that not all driver steering override actions are deliberate, there is a risk of a negative effect on the benefit of the active safety system. The alternative strategy would be to allow the driver to gradually override a steering intervention and cooperatively share control with the steering assist (13)(14).

This work assumes a vehicle equipped with an Electric Power Assist Steering (EPAS) System including an electronically controlled assist motor. During normal steering operation, the assist torque generated \( T_{\text{assist}} \) by the motor is mainly determined by the driver’s steering torque measured at the torsion bar \( T_{\text{tr}} \). During autonomous steering interventions, an algorithm computes the motor torque required to follow the intended trajectory. In this paper, it is assumed that the \( T_{\text{assist}} \) is superposed to the torque request of the autonomous steering system, here referred to as the overlay torque. As a consequence, there will be a reaction torque affecting the \( T_{\text{tr}} \) if the driver would try to steer the vehicle during an intervention.

The reaction torque due to a torque overlay is necessary given a conventional steering system with a mechanical coupling between the steering rack and the steering wheel. Since, steering a vehicle autonomously requires automatic control of the steering wheel movement; the driver’s hands will feel the movement and hence, cause a reaction torque. The level of reaction torque depends mainly on the level of the requested torque overlay and to the degree the driver resists the automatic steering. If the driver is able to counter steer without experiencing much of a reaction torque, the effectiveness of an automatic steering intervention will be low (e.g. the low effect of haptic feedback in (20)). The overlay torque magnitude, as well as its characteristics will influence the driver steering interface; it is hypothesized that a driver would likely take a swift response to an applied torque with very high change rates, compared to a very smooth one. The desired driver reaction torque to an applied overlay torque depends on the driving situation and application.

In this paper, it is assumed that the vehicle is equipped with an LKA system which requests steering interventions near the lane markings to prevent lane departures. If LKA requests intervention in a curve on the inner side of the lane, it is assumed that the magnitude of the torque overlay should be lower compared to an intervention on the outer side of the lane. This is a probable scenario since many drivers tend to cut curves when driving (c.f. “curve cutting” (23)). Completely suppressing an intervention (i.e. not activating the intervention at all or aborting the intervention completely) in such situations can however be problematic when the road geometry (i.e. curvature) changes continuously. It could lead to reduced performance and lower real life safety benefit.

A driver steering override strategy aims to deal with the above mentioned aspects of driver/system interaction. A successful strategy needs therefore to delicately balance the following objectives:

- Provide acceptable steering feel when interacting with the autonomous steering.
- Handle specific situations like deliberate cutting of curves or obstacle avoidance dictating lane departure (c.f. (20)).
- Provide benefit whenever the system intervention is required, i.e. make sure the vehicle will travel near the intended path in case the driver is not deliberately counter steering but still provides typical steering wheel resistance.
- Allow the driver to easily handle a non-desired applied torque (e.g. generated due to erroneous sensor data).

3. DRIVER STEERING OVERRIDE STRATEGIES

The driver override strategy rationale is schematically shown in Fig. 1 and Fig. 2. Fig. 1 depicts the inner angle control loop typically used in automotive path control concepts (23)(24). It consists of:

- An angle controller with input, the steering angle difference between the pinion angle request \( \delta_r \) (from the LKA function) and the actual measured pinion angle \( \delta \) of the vehicle.
- A saturation block, necessary to get full effect of scaling down the torque request \( T_r \) (the controller will otherwise compensate for the scaling by increasing the torque request due to a growing angle error and/or integral action).
- An override block determining a scaling factor \( a \) and a scaled torque overlay request \( T_{\text{scaled}} \). A more detailed view of this block is shown in Fig. 2 where the signal \( C \) is the instantaneous curvature of the road, and \( D_{\text{max}} \) is a signal reflecting the direction of the intervention. Combining the information of \( D_{\text{max}} \) and \( C \), determines whether the steering intervention is requested on the inside or outside of a curve.
- The vehicle plant-system at which the scaled overlay torque is applied. Two measured signals are shown as
outputs from this block; the torsion bar torque, \( T_{tb} \), and the vehicle yaw rate, \( \dot{\psi} \).

The override rationale adapts the overlay torque requested by the active safety steering system, according to the driver’s steering reaction. In case of a driver steering override, i.e. when the driver augments torque to the steering wheel, the measured torsion bar reaction torque \( T_{tb} \) will start to change. At the same time, a scaling factor \( \alpha \) is being multiplied with the steering torque request \( T_r \). A consequence, the impact of the steering intervention is adapted according to the override strategy.

\[
\alpha = \begin{cases} 
0 & \text{if } \| T_r \| < \alpha_{\text{deadband}} \\
\frac{T_r}{T_{tb}} & \text{otherwise}
\end{cases}
\]

Fig. 1 Schematic overview of the driver override strategy.

2.1. Strategy No. 1

Strategy No. 1 constitutes the driver override principle used in the LKA of the production Volvo V40. The solid line in Fig. 3 shows scaling factor \( \alpha \) as a function of the measured torsion bar reaction torque \( T_{tb} \). The deadband around zero torque serves to avoid driver interference with the requested steering manoeuvre in cases where the driver is not deliberately counter steering. Thus, the deadband should be wide enough to reflect maximum driver reaction torques due to the torque overlays.

The expected torque to negotiate a curve with radius \( R \) and travelling speed \( V \) is calculated using the steering torque gradient (25) of the vehicle (Nm/g); this steering metric determines the torque that has to be applied on the steering wheel to achieve certain lateral acceleration. A look-up table was generated with offline simulations for a range of travelling speeds and steering gradient (25) of the vehicle (Nm/g).

In cases where the driver is interfering with the autonomous steering request when the steering intervention is generated to avoid leaving the lane on the outside of a curve, the scaling factor described by the solid line in Fig. 3 would potentially be too low for the system to provide beneficial overlay torque levels. This is due to the effect of the vehicle’s steering torque gradient (Nm/g) (25) causing the scaling factor to reach low levels just by driving along a path with a curvature similar to the one of the road. To deal with this effect, the deadband around zero torsion bar torque where no scaling is carried out is asymmetrically moved according to the lines shown in Fig. 3.

Another scenario related is interventions given on the inside of a curved road. As the minimum radius of the curve decreases, driver’s tendency to cut the curve increases. Steering interventions in these cases will be experienced as undesirable. To avoid this problem while keeping the system benefit in curves with moderate to large radius, the scaling factor is being modified according to Fig. 4. I.e., the overlay torque will always be scaled with a number less than 1 even for small torques applied to the steering wheel by the driver. Additionally, the minimum scaling factor will also be reduced as curve radius is decreasing.

The override rationale adapts the overlay torque requested by the active safety steering system, according to the driver’s steering reaction. In case of a driver steering override, i.e. when the driver augments torque to the steering wheel, the measured torsion bar reaction torque \( T_{tb} \) will start to change. At the same time, a scaling factor \( \alpha \) is being multiplied with the steering torque request \( T_r \). A consequence, the impact of the steering intervention is adapted according to the override strategy.

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\frac{T_r}{T_{tb}} & \text{otherwise}
\end{cases}
\]

Fig. 2 Schematic overview of the scaling of the requested overlay torque as a function of torsion bar torque \( T_{tb} \).

2.2. Strategy No. 2

Strategy No. 2 is in conceptual phase in the Volvo development process. It adopts certain principles of strategy No. 1 with extra features:

- Scaling factor generation using speed and curvature dependence,
- deadband creation (c.f. strategy No. 1) according to the expected torque to negotiate the given curve,
- and intervention fade-out.

The activation logic is governed by 8 states. Those states derive from 3 decision classes: 1) if it is an inner or outer curve intervention, 2) if the driver is using less or more torque than expected to negotiate the given curve for the vehicle’s travelling speed, 3) and if the driver resists or complies with the intervention. Those 3 binary cases formulate 8 states; according to state the requested torque \( T_r \) (c.f. Fig. 1) can go through the override block unmodified, scaled down, faded-out or scaled down and faded-out.

The expected torque to negotiate a curve with radius \( R \) and with the travelling speed \( V \) is calculated using the steering torque gradient (25) of the vehicle (Nm/g); this steering metric determines the torque that has to be applied on the steering wheel to achieve certain lateral acceleration. A look-up table was generated with offline simulations for a range of travelling speeds. The decision whether the driver complies or resists the intervention derives from the magnitude (positive/negative and
level) of the product of $T$, and $T_F$ (c.f. Fig. 1). The dependence of the scaling factor $\alpha_{SD}$ on the cornering radius $R$ and travelling speed $V$ is displayed in Fig. 5.

An intervention i) can be scaled down, if the driver is applying torque outside the deadband (c.f. Fig. 5) and ii) faded-out if the driver resists the intervention. The i) scale down principle generates the $\alpha_{SD}$ and ii) the fade-out generates the $\alpha_{FO}$ factor. The $\alpha_{SD}$ is time-dependant; when there is fade-out request, after time $t_{F_{\text{fadeout}}}$, the $\alpha_{FO}$ starts to linearly decrease from 1 to 0. Thus, if the driver continuously resists, the intervention, the $\alpha_{FO}$ will eventually become 0. The product of $\alpha_{SD}$ and $\alpha_{FO}$ determines the final scaling factor $\alpha$, equivalent to strategy No. 1 (c.f. Fig. 2).

A logical transition from true to false for the fade-out request will result the $\alpha_{FO}$ to linearly increase from its current value to 1.

![Fig. 5 The scaling factor $\alpha_{SD}$ dependence on road radius and travelling speed. The vertical line designates the expected steering torque to negotiate the curve with radius $R$ when the travels with speed $V$. A deadband is created around the expected torque (vertical line).](image)

### 2.2.1 Steering intervention states

The 8 states deriving from the 3 activation classes and 1 additional state (0) when the driver’s torque is within the deadband (c.f. Fig. 5) are depicted below:

0. The driver’s torque is within the deadband (c.f. Fig. 5). Decision: keep scaling factor $\alpha$ to 1.
1. The driver is using more torque than expected and complies with the outer curve intervention. Decision: scale down (driver is active).
2. The driver is using more torque than expected and complies with the inner curve intervention. Decision: scale down and fade-out (not relevant state since LKA will suppress $T_c$ to 0).
3. The driver is using more torque than expected and resists the outer curve intervention. Decision: scale down and fade-out (not relevant state since LKA will suppress $T_c$ to 0).
4. The driver is using more torque than expected and resists the inner curve intervention. Decision: scale down and fade-out the intervention (driver is cutting the corner).
5. The driver is using less torque than expected and complies with outer curve intervention. Decision: do nothing (driver needs the intervention).
6. The driver is using less torque than expected and complies with the inner curve intervention. Decision: scale down (driver is active).
7. The driver is using less torque than expected and resists the outer curve intervention. Decision: scale down and fade-out the intervention (drive steers towards the outside of the curve).
8. The driver is using less torque than expected and resists the inner curve intervention. Decision: do nothing (driver follows-needs the intervention).

The Strategy No. 2 employees, rate limiters and filters to provide smooth transition between states for the $\alpha_{SD}$, $\alpha_{FO}$ and $\alpha$.

### 3. METHOD

The two strategies have been evaluated in the Volvo Car Traffic Simulator (VCTS) in Matlab/Simulink. The simulated vehicle is a 7 DOF Volvo S60 incorporating non-linear tires and a sophisticated EPAS model consisting of a steering column, a rack–pinion assembly and the assist motor, controlled through the ECU model with speed-dependent power-assist maps. The motor delivers the rack assist force through a belt-drive/ball-mut gearbox.

![Fig. 6 First scenario: inner curve negotiation with steering torque ramp-up until $acc = 0.82 \text{m/s}^2$. Strategy No. 1, strategy No. 2 and without LKA are correspondingly the “1”, “2” and “No” cases. The driver resists intervention with LKA enabled.](image)
strategies. All 3 scenarios use the same road; the road has 2 lanes with a total width of 8 m and consists of a 20 m straight segment and 180 m curved segment with 1500 m constant radius (positive to the left). A longitudinal controller maintains the desired vehicle speed \( V = 80 \text{ km/h} \) for all 3 scenarios. At the end of the straight road segment, linearly increasing torque is applied on the steering wheel until the vehicle achieves a target lateral acceleration \( \text{acc}_y \); then it freezes the torque. This torque, through the 2nd order dynamics of the steering column will generate the torsion bar torque \( T_{tb} \) which in turn is used in the EPAS to determine the power-assist levels. A driver model with neuromuscular features which can interact with the steering wheel using torque (c.f. (26)(27)), could be used in a later stage of this work for verification.

5. RESULTS

The three scenarios of an inner, outer and inner curve negotiation with the driver resisting the intervention \( T_{r} \) are correspondingly displayed in Fig. 6, Fig. 7 and Fig. 8. Each figure illustrates three simulations; the two strategies “1” and “2” and one “no” LKA support. The subplots (from top to bottom) show: i) the vehicle’s trajectory with respect to the road (the simulation time is overlaid on the vehicle), ii) the pinion angle, iii) the torques \( T_{r}, T_{b} \) (c.f. Fig. 1), iv) the actual lateral acceleration \( \text{acc}_y \) of the vehicle and the “expected” (according to the travelling speed \( V \) and curvature), and v) finally the scaling factor \( a \) (Fig. 2) and \( \alpha_{pd} \) and “State” only for strategy No. 2 (the overlay number depicts the state). The overall picture of the three scenarios clearly display the influence of the driver override strategy to the vehicle’s trajectory.

In the first scenario in Fig. 6, the open loop torque applied on the steering wheel is approximately 30% greater in magnitude than the expected torque to negotiate the given curve. Thus, without LKA (case “No”) the vehicle will drift out of lane. In the cases “1” and “2” the LKA function will start requesting \( T_{r} \) at around 3.7 s to prevent an imminent road departure. The scaling factor for strategy No. 1 (case “1”) is considerably reduced since the intervention is on the inside of a curve where the overlay torque will always be scaled down even for small torques \( T_{b} \) (c.f. Fig. 4). For case “2” though, the \( T_{b} \) is barely exceeding the deadband. Since, this is an inner curve and the driver is steering outwards, this corresponds to state 4. The fade-out command remains issued for \( t_{f/Mode} \) (from 3.7 to 4.2 s), and the \( \alpha_{pd} \) starts to decrease, diminishing the \( T_{r} \) effect through \( \alpha \).

In the second scenario in Fig. 7, the torque applied on the steering wheel is negative, driving the vehicle outwards. Without LKA the vehicle will drift out of lane. In the cases “1” and “2” the LKA function will start requesting \( T_{r} \) at around 2.2 s to prevent an imminent road departure. The scaling factor \( a \) in case “1” has a value close to 1, since the intervention is on the outside of the curve and \( T_{b} \) is small in magnitude. Thus, the intervention is not scaled down, and the resulting overlay torque is “enough” to keep the vehicle within the road limits. For case “2”, the \( T_{b} \) is off the deadband zone, since the expected torque to negotiate this curve is positive and \( T_{b} \) is negative. The \( T_{b} \) is therefore less than expected for an outside curve intervention, corresponding to state 7. The rationale for this state is that driver wants to steers...
outwards. State 7, requests the overlay torque to be scaled-down and faded-out. It can be noted, that before the \( \alpha_{SD} \) starts to decrease, the \( \alpha \) and in fact the \( \alpha_{SD} \) is already around 0.4. The decreasing \( \alpha \) diminishes the overlay torque and the vehicle drifts out of lane.

Finally, in the third scenario in Fig. 8, the open loop torque applied on the steering wheel is approximately 7% greater in magnitude than the expected torque to negotiate the given curve. Without LKA the vehicle drifts out of lane. In cases “1” and “2” the LKA function will start requesting \( T_{r} \) around 4.2 s to prevent an imminent road departure. The scaling factor for strategy No. 1 is reduced (again as in the first scenario) since the intervention is on the inside of a curve where the overlay torque will always be scaled down even for small torques \( T_{o} \) (c.f. Fig. 4). For case “2” though, the \( T_{o} \) is within the deadband corresponding to state 0. Thus, \( \alpha \) remains 1 and \( T_{r} \) generates an unmodified overlay torque. This results the vehicle to stay within its intended lane.

5. DISCUSSION

The current paper compares Volvo’s current and a concept driver steering override strategy during LKA interventions. The driver steering override theme evaluates the driver’s interaction with the vehicle and modulates accordingly the level of intervention. Both strategies quantify the driver’s activation by means of steering torque and road/vehicle information. The two strategies have been evaluated in the Volvo Car Traffic Simulator (VCTS) in Matlab/Simulink. Three different lane-drift scenarios have been devised to enable the comparison between the two strategies. The results presented clearly showed that the override strategy can majorly influence the efficiency of LKA.

Reflecting the objectives described in the Problem Statement section into the results, then it can be seen that both strategies fulfill the requirements for an ADAS system. Both strategies are able to provide a steering feedback without discontinuities when interacting with autonomous steering. They can both cope with situations like deliberate cutting of curves or obstacle avoidance and also allow the driver to counteract non-desired overlay torques (e.g. due to erroneous sensor data). They can finally, keep the vehicle on the intended path whenever the system intervention is required (within the vehicle’s physical and LKA function’s limits).

It has to be noted that the LKA function (not described here), as well as driver override strategy No. 2 are in concept phase and do not reflect any Volvo functionality in production. The control principle and corresponding states for strategy No. 2 are under development; the same stands for the tuning of the whole override theme. Objective in-vehicle tests, with extended subjective rating, will determine the features and final tuning adopted in Volvo’s next generation driver override strategy.

Concluding, the override strategy has a decisive influence on the LKA benefits, depicting therefore the need for careful design and rigorous testing.

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