

Reduction of Steering Effort in the Event of EPAS Failure using Differential Braking Assisted Steering

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ABSTRACT

Electric Power Assisted Steering (EPAS) is widely adopted in modern vehicles to reduce steering effort. It is probable that some EPAS systems will experience a shutdown due to reliability issues stemming from electrical and/or electronic components. In the event of EPAS failure, power assist becomes unavailable and the steering system reverts to a fully manual state, leading to excessive steering torque demands from the driver to maneuver the vehicle at lower speeds, i.e., under 30 mph. This situation has resulted in dozens of reported crashes and several OEM safety recalls in the past few years. Inspired by recent work which utilizes independent driving torque of in-wheel-motor vehicles to reduce steering torque, this paper proposes the use of Differential Braking Assisted Steering (DBAS) to alleviate steep increases in steering torque upon EPAS failure. DBAS requires software upgrades with minimal hardware modification to EPAS, which is preferable for a backup system. A preliminary evaluation of DBAS is carried out using simulations in CarSim. Results show that DBAS reduces steering torque to similar levels as EPAS in all of the steady state, transient and urban driving scenarios investigated. The results also show that DBAS triggers vehicle speed reduction and oversteer, the latter of which is in conflict with Electronic Stability Control (ESC) which is designed to inherently prevent oversteer. Since ESC is typically crucial at higher speeds, this conflict can be avoided by employing DBAS only at lower speeds where steering assist is most needed. This paper motivates further study of DBAS for emergency safety in the event of EPAS failure.

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INTRODUCTION

Power assisted steering systems are used in the vast majority of modern vehicles. They apply assistive force to the steering system in order to reduce driver steering effort. Electric Power Assisted Steering (EPAS) has many advantages over the conventional Hydraulic Power Assisted Steering (HPAS), with regard to fuel efficiency, control flexibility, and environmental compatibility [1]. As a result, EPAS is rapidly replacing HPAS in modern-day vehicles. Recent trends towards vehicle electrification and autonomous driving have also facilitated the rapid adoption of EPAS.

Despite the many advantages over HPAS, reliability issues of EPAS are also raising public concerns. Electrical and/or electronic component defects may cause EPAS failure and shutdown. According to NHTSA reports [2, 3, 4], excessive steering effort is demanded from driver in the event of EPAS failure, resulting in dozens of crashes and injuries, and a couple of OEM safety recalls in recent years [5, 6, 7, 8, 9]. Many efforts have focused on developing fault tolerant features for electrical and/or electronic components of EPAS to prevent failures from happening, e.g., [10, 11, 12, 13]. However, there is no work in the open literature or patents addressing safety measures after EPAS shutdown. OEMs have argued that, in the event of EPAS failure, the driver is still capable of controlling the vehicle, since mechanical linkages remain intact and the system merely reverts to manual steering state. However, in reality, steep increase of

steering effort may cause driver panic and loss of vehicle control, as in some of the reported crashes [14]. Therefore, it is of immense importance to incorporate protective measures to alleviate driver's steering effort in the event of EPAS failure.

To meet this objective, the primary contribution of this paper is in proposing a backup system for EPAS called Differential Braking Assisted Steering (DBAS), and evaluating it through simulations. As the name implies, DBAS employs differential braking to help reduce driver steering effort upon EPAS failure. DBAS is inspired by Differential Drive Assisted Steering [15, 16, 17], which utilizes the independent driving torque feature of in-wheel-motor vehicles to alleviate steering effort, with a goal to replace EPAS (or HPAS) in such vehicles. However, unlike Differential Drive Assisted Steering, DBAS makes use of differential braking capabilities which are available in virtually all modern-day vehicles. Furthermore, the purpose of DBAS is to serve as a backup safety system, not to replace EPAS like Differential Drive Assisted Steering.

It is worth mentioning that differential braking has been exploited for various purposes related to vehicle control. A prime example is Electronic Stability Control (ESC), which is now a must-have feature for new vehicles sold in the United States. ESC uses differential braking to counter understeer and oversteer, thus keeping the vehicle stable during steering maneuvers [18, 19]. Differential braking has

been proposed by Pilutti et al. to correct driver steering input for an unintended road departure system [20,21]. Differential braking has been proven to reduce turning radius in long-wheelbase vehicles [22]. It can also serve as backup for Steer-by-Wire systems when the steering motor fails and the front wheels cannot steer [23].

The rest of this paper is organized as follows. Section 2 introduces DBAS, together with its control strategy, followed by a presentation of simulation-based case studies carried out in CarSim to evaluate DBAS performance in various realistic safety-critical driving scenarios. In Section 3, a vehicle dynamics model combined with CarSim simulation results are used to demonstrate reasons why DBAS reduces steering effort. Potential side effects of DBAS and possible solutions are also discussed, as a motivation for further study on driver reaction to DBAS as a backup safety strategy. Conclusions and future work are then presented in Section 4.

CONTROL STRATEGY AND PERFORMANCE EVALUATION OF DBAS IN CARSIM

Control Strategy of DBAS

The main objective of DBAS is to reduce driver steering torque in the event of EPAS failure. Since the best case scenario is to reduce steering torque to the same levels as when EPAS functions well, it is natural to choose it as a reference. In DBAS, feedback control is designed to minimize the difference between reference and driver's actual steering torque through differential braking, as illustrated in Figure 1. Measurements of vehicle speed V and lateral acceleration A_y from vehicle sensors are used to determine reference steering torque T_r from the reference steering torque map. The obtained value of T_r is then compared with driver input steering torque T_{sw} , resulting in error signal T_e . A PI controller operates on T_e to produce T_e' , which is then used to determine the differential braking command T_b . The sign of T_e' decides whether brakes are to be applied to the left or right wheels of the vehicle. For example, if the driver is making a right turn upon EPAS failure, and the steering torque is larger than the reference, making T_e' greater than zero, brakes will be applied to the right wheels. The brake control gains are also speed-dependent. If vehicle speed is higher than a threshold, gain of right front brake K_{RF} will become the only non-zero value in command T_b , i.e., applying only right front brake. Otherwise, both K_{RF} and K_{RR} will be non-zero (i.e., applying both right front and right rear brakes) in order to amplify the effect of differential braking at lower speeds. Finally, the brake system receives the command T_b and actuates the brakes accordingly. The feedback loop between the vehicle (plant) and DBAS controller minimizes the error T_e continuously.

The torque map widely used for steering feel design is transformed and put to use for DBAS [1,15]. The reference steering torque map can be created based on a fully functional EPAS through standard tests for vehicle handling evaluation, such as weave test and double lane change test [24,25]. A 2D map, shown in Figure 1, is developed by setting a constant ratio of steering torque to lateral acceleration (e.g., k_1) at a certain speed (e.g., V_1) based on the EPAS-on case (i.e., EPAS is fully functional) as shown in Figure 2. Variable ratio is not considered because steering feel is not the primary concern upon

EPAS failure. A flatter slope in on-center zone, though results in less "road feel", makes the difference larger between actual steering torque upon EPAS failure (i.e., the EPAS-off case) and the reference steering torque as soon as driver starts steering, thus quickening system response. Without compromise in system performance, further improvement of reference steering torque map may consider mimicking EPAS torque assist feature. Lateral acceleration is chosen over steering angle as the measure of map due to hardware concerns. According to OEM document [14], steering angle signal comes from either angle sensor mounted on steering column or motor position sensor within EPAS assist motor. For the latter configuration, measurements of steering angle may become troublesome to get access to upon EPAS failure. Since lateral acceleration is also commonly used in vehicle handling evaluation, it is considered a better choice for DBAS in this paper.

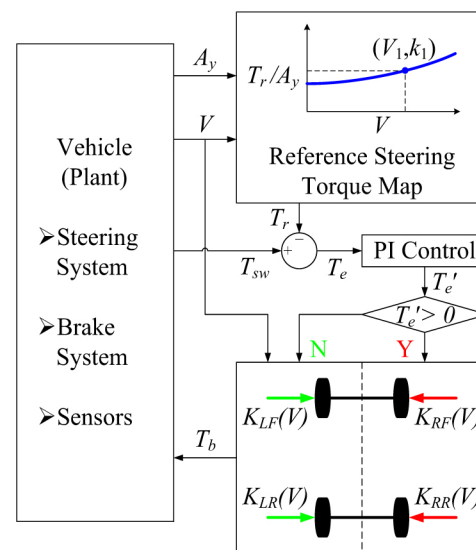


Figure 1. Block diagram of DBAS control algorithm

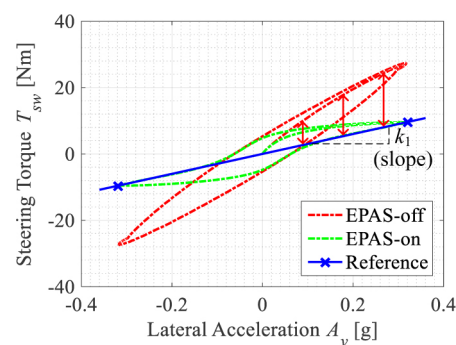


Figure 2. Reference steering torque map at V_1 . The arrows denote the difference between actual and reference steering torque when driver starts steering upon EPAS failure.

According to DBAS control strategy, measurements of vehicle speed, lateral acceleration, and steering torque, and access to brake system are only required for DBAS to realize its function. In the event of EPAS failure and shutdown, vehicle speed and lateral acceleration sensors and brake system will not be affected. Minor hardware modification, i.e., an extra signal output cable, is needed to enable the

steering torque sensor to output its signal to the DBAS control unit. Therefore, as a backup system, DBAS only requires software upgrades and minor hardware modification.

CarSim Simulation Configuration

CarSim is widely used in the automotive industry for vehicle system-level simulation and analysis. Since CarSim has detailed and accurate vehicle models already built-in, it can be used to evaluate the performance of the proposed DBAS system in simulations. The modeling process of vehicle and steering system in CarSim involves calibration of model parameters for realistic steering torque results. Steering system parameters of an actual passenger vehicle and its steering torque test data for two cases (i.e., with and without EPAS assist) are provided in report [26], and are used to calibrate parameters in CarSim through simulations of a 30-meter steady state circle test and static steer test. The calibration of CarSim vehicle model using actual system parameters and test data allows more realistic evaluation of DBAS performance in simulations.

The selection of driving scenarios for simulation and DBAS evaluation considers whether they are safety-critical in the event of EPAS failure. Report [26] listed common steering maneuvers driver may encounter, including 1) static steer; 2) parking lot maneuvers; 3) intersection turns; 4) curvy roads with speed limits at or under 25 mph; 5) curvy roads with speed limits at or under 35 or 45 mph; 6) highway exit ramps; 7) highway driving at or above 60 mph, etc. According to investigation report [27], steering maneuvers at or under 30 mph may induce excessive steering torque demands upon EPAS failure; test data in [26] confirms this statement, showing that EPAS usually provides more than 70% of the total steering torque in maneuvers within this speed range. This means that driver needs to apply three times more effort upon EPAS failure. Not every driver has the ability to handle this steep increase well, in which case he/she may lose control of the vehicle. Road designs also have an influence on steering torque applied by driver. For instance, highways or roads with higher speed limits are usually not designed with sharp turns. The designed lateral acceleration levels are usually under 0.2g. Hence steering torque demands are not high even when EPAS fails. Based on this fact, the 5th and 7th scenarios above are excluded. Static steer test is also excluded, since differential braking inherently cannot help reduce steering torque at zero speed. However, since no accidents tend to happen when vehicle is at standstill, the inability of DBAS to handle this scenario is acceptable.

The selected driving scenarios and their parameters are listed in Table 1, together with the main purpose of considering each scenario. Note that serpentine driving course, which simulates curvy roads with lower speed limits, is considered here because it has been used before for similar testing of vehicle maneuverability upon HPAS failure [28]. U-turns represent the extreme case of parking lot maneuvers, which usually involve low-speed sharp turns. Driver control in CarSim is set to follow the designed path and speed of each of these driving scenarios. This set of configurations help demonstrate whether DBAS can reduce steering torque and maintain control of the vehicle upon EPAS failure.

Table 1. Selected driving scenarios for CarSim simulation

Scenario	Path	Speed	Lateral Acc.	Purpose
Highway Exit Ramps	500 ft. diameter circle	30 mph	0.25g	steady state response
Serpentine Driving Course	200 ft. radius ¼ circles	30 mph	0.3g	transient response
Intersection Turns	25 to 100 ft. radius	< 20 mph	< 0.4g	most common maneuver
Parking Lot U-turns	minimum turning radius	< 10 mph	< 0.25g	ground friction effect

CarSim Simulation Results

In this subsection, the driving scenarios listed in Table 1 are simulated, and steering torque results are compared among three cases, namely, EPAS-off, EPAS-on and the proposed DBAS. The trajectory following capability of DBAS is also illustrated.

Highway Exit Ramps

Figure 3(a) shows vehicle trajectory on highway exit ramp. From zoom-in view it can be seen that the driver is able to follow the designed path with a maximum deviation of 0.25 m when DBAS is working, which indicates that the vehicle is stable and sufficiently under control. Figure 3(b) shows the simulation results of steering torque, the primary measure of DBAS performance. When EPAS is on and off, steering torque goes from a steady-state value of 8.45 to 21.43 Nm, respectively. If EPAS fails suddenly, this 150% increase in steering torque could take the driver by surprise and lead to loss of control. However, with DBAS active, steering torque is reduced to the same level as EPAS, thus proving its potential to act as an effective backup system in this scenario.

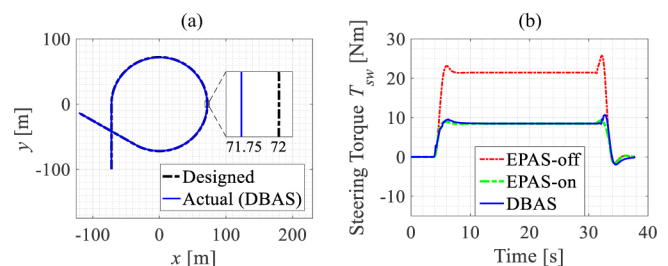


Figure 3. (a) Vehicle trajectory on highway exit ramp; (b) simulation results of steering torque

Serpentine Driving Course

As mentioned in the preceding section, the serpentine driving course (illustrated in Figure 4(a)) has been used in a test to examine whether drivers are capable of controlling the vehicle after total failure of HPAS [28]. Therefore, it is reasonable to apply it to the case of EPAS failure in order to evaluate the performance of DBAS. The serpentine