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Citation for the original published paper (version of record):

Klomp, M., Bruzelius, F., Bergström, O. et al (2024). Steer-by-wire -- The challenge of angles and torque. Lecture Notes in Mechanical Engineering: 771-781.
http://dx.doi.org/10.1007/978-3-031-66968-2_76

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# Steer-by-wire – The challenge of angles and torque

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**Abstract.** The introduction of Steer-by-wire systems for cars is believed to bring a wide range of advantages ranging from production simplifications to passive safety and advances in active safety. The intense work with autonomous driving has paved the way for redundancy and systems safety needed to introduce steer-by-wire to the broad market. This paper explores some of the fundamental aspects of mechanically disconnecting the driver and hand wheel from the vehicle and the road wheel, such as variable steering ratio and generation of haptic torque feedback. Simple strategies are developed and tested on test track in a prototype vehicle. Initial tests suggest that the simple strategies might suffice.

## 1 Introduction

Since the dawn of the automobile, the steering input from the driver has been mechanically linked to the front wheels. This has traditionally been the case also with ships and airplanes. With by-wire technology, however, the mechanical linkage between the driver/helmsman/pilot and the directional control surfaces is replaced with an electronic connection. By-wire technology allows both the relationship between input and output, as well as the haptic feedback to the driver to be freely designed such that maneuvering the vehicle is simplified and made safer. In airplanes, these capabilities are used to make it easier to maneuver the plane and to avoid dangerous and hard-to-control conditions such as avoiding overloading or stalling the aircraft. This is done via a so-called flight envelope protection system allowing pilots full control without exceeding the aircraft's limits. Fly-by-wire systems also allow for the development of aircraft with relaxed directional stability in order to improve maneuverability, such as many modern fighter aircraft. These aircraft would not be possible to fly without the use of fly-by-wire systems that continuously work to stabilize the aircraft,[5].

For the automotive industry, the steer-by-wire introduction is yet to be seen with only a handful of production cars available. A step in the direction of steer-by-wire was the broad introduction of electrically assisted steering systems replacing hydraulic systems. With the introduction of electrically controlled assistance, it was possible to control the haptic torque, isolating the driver from unwanted road disturbances and steering geometry influence. The work in [4] illustrates how the transition from an electrically assisted steering system could be made to steer-by-wire systems from an algorithmic perspective.

One of the main drives for introducing steer-by-wire is the many benefits it could bring, [8]. From a vehicle manufacturer's perspective, this can be a system that is easier to handle for variants such as left- and right-hand side steered vehicles. Other advantages are packaging and passive safety benefits with not having to deal with the steering intermediate shaft. The potential increase in energy consumption is not expected to be substantial as empirical studies suggest that the driver's energy added to handle a vehicle with a steering column is on the order of $5 - 10\%$ of the total energy needed.

From a user perspective, one may state possibilities for improved integration with advanced driver-assistance system (ADAS) as well as completely disconnecting the driver in autonomously driven cars. This because steer-by-wire allows for intervention without influencing the driver's input. Examples of when this could be beneficial are skid stabilization, evasive maneuver assist, or keeping the car on the intended trajectory during braking on an uneven (split) friction surface. A future introduction of autonomous cars has also pushed the development of redundancy which in turn also may be seen as an enabler for steer-by-wire systems. Other benefits are variable steering ratio, discussed extensively in this paper, improving both maneuverability and stability for the driver. The reduced steering wheel range enabled by the variable steering ratio also allows for different steering wheel design and don't require the driver to change the hand positions during steering [10]. Finally, it is likely there will be further benefits that we cannot even imagine today that will arise from the possibilities provided by steer-by-wire.

The safety of steer-by-wire systems represents a major challenge for vehicle manufacturers. More explicitly, system safety and legal compliance are challenges and identification of safety goals such as the one presented in [7,9] needs to be developed in technical safety concept and fallback strategies.

In this short study, some proposals for handling the additional degree of freedom introduced by the steer-by-wire system are implemented in a test vehicle and tried out on a test track. A strategy to handle the discrepancy between hand and road wheel angles is tested. Simple data-driven haptic strategies are tested along with different approaches to implementing variable steering ratios. The work is based on two student thesis works in [1] and [2].

## 2 Experimental setup

To test algorithms and concepts in a realistic setting, both a test rig and a test vehicle were developed. The test vehicle was taken as a standard production vehicle, left side steered, equipped with double command pedals. The electrically assisted steering system was augmented with an external torque request, and to that an angle controller, such that a road wheel angle could be requested through the interface.

An additional hand wheel was added on the right-hand side of the car, mounted to an electric feedback motor. The right-hand side hand wheel was connected to the rest of the car, specifically to read the vehicle speed, and road wheel (pinion) angle and request a road wheel angle through the interface described above. A photo of the interior of the test vehicle is given in the left of figure 1.

**Fig. 1.** Left: Test vehicle with the two steering systems. Right: Desktop test rig with the feedback motor and the steering rack

The arrangement was such that a torque input on the left-hand side hand wheel interrupted the external torque interface of the steering rack immediately. This made the test vehicle a safe platform for testing on test tracks with a stand-by co-driver on the left-hand side, ready to intervene if any anomaly occurred. There were many performance limitations present in the test vehicle, but it still provided for a good test platform to test the ideas that were explored in this study.

The test rig is an arrangement intended to mimic the implementation in the test vehicle. Hence, the same hand wheel and feedback motor are attached to a stand. The motor attached to the hand wheel via a gearbox is controlled using a prototype ECU. The setup was complemented with the same type of steering rack used in the test vehicle, using the same interface. The complete setup is shown in the right of figure 1.

## 3 Problem formulation

The problem of controlling the hand wheel in a, to the user, consistent and predictable manner can be divided into to fields; the haptic feedback torque and the steering ratio. These are further explained in the following sections.

### 3.1 Haptic feedback torque

The haptic feedback torque is the torque actuated by the feedback motor mechanically connected to the hand wheel of an steer-by-wire system. The purpose is to give the driver feedback on resistance torque to motions and torque applied by the driver. For conventional steering systems, the torque felt in the hand wheel also originates from the environment and what the tire is interacting with, such as closeness to complete sliding of the steered tires. Much of this feedback is considered important for the driver to sense the current state of the vehicle and tire motion and guide accordingly. Other torques that originate from the environment are not desired to be felt, such as periodic vibrations caused by imbalances of the road wheels.

For steer-by-wire systems, all haptic torque needs to be generated by a control algorithm sending requests to the feedback motor. Haptic and reactions to torque are strongly connected to human expectations. This is also why steer-by-wire systems most often aim to replicate conventional systems in this regard. However, with the flexibility of controlling the entire sensation, one can easily choose to only replicate the desirable and leave all undesirable torque-generating phenomena isolated from the driver. In this study, the focus is on model based feedback, where several of the parameters can/should be adapted to the road condition in order to more accurately reflect the road conditions.

The part of the torque felt in the hand wheel through a conventional steering system that is believed to be beneficial to the driver's ability to steer the vehicle can be modeled through the first principal models of the (conventional) steering system and the tire-to-road interaction, such as [3]. This will capture the components of the torque that we expect from a conventional system. However, in such a system, being a hydraulic or electrically assisted system, a vital part of the torque generation is governed by designed control rather than physics. This motivates a more empirical approach to the problem of replicating torque by simple algebraic expressions fitting measured data from conventional systems.

In the following we will go through some of the components of the torque and how we have chosen to model them with simple algebraic expressions rather than models of the physics. These are to a large extent organized in how they appear to the driver, rather than the physics behind them.

**Base torque** is the torque that we feel in the hand wheel that originates from only considering a vehicle steering system and the steady state aligning torque. From measurements of the aligning torque under these conditions, a shape was identified. This shape has the hand wheel angle (the pinion angle) and the vehicle speed a independent variables. The shape is described by a spline function mapping a second-order polynomial function in the angle for low angles over to a linear function that finally connects to a second second-order polynomial function to capture the typical drop of torque experienced when the aligning torque (and force) of the front tires starts to be saturated. The connecting points determine the parameters of the involved functions and are made dependent (quadratically) on the vehicle's longitudinal speed. A realization of the functions can be seen for two speeds in figure 2.

**Friction torque** is a central component to the steering feel and aids the driver in calmer driving by enabling a small resistance to rest against while maneuvering the vehicle. In a conventional steering system, the friction felt in

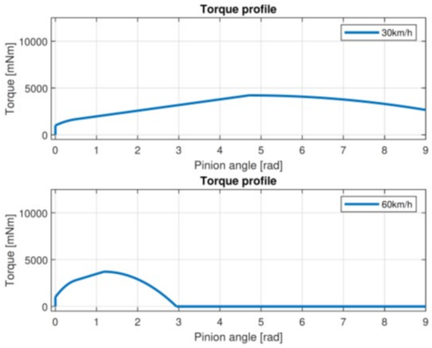

**Fig. 2.** Torque generation form the base torque and friction contribution for two different vehicle speeds

the hand wheel originates from a long line of mechanical components and interactions such as in the rack motion, the bearings of the steering column, and electrically in the assistance motor. Here, the friction torque is modeled as a tanh function of the pinion angle rate, enabling easy implementation and a simple stiffness adjustment to cope with sample rates and the numerical stability of the algorithm.

**Damping torque** is the torque originating from a hand wheel's motion (first derivative of angle). The damping of the hand wheel is important in dynamic maneuvers of the vehicle and may limit the driver to do too aggressive angle changes, and makes the vehicle behave calmly if the hand wheel is released after a curve.

In a steer-by-wire system, there is a need to limit the driver's ability to steer more than the system is capable to actuate. Explicitly, this means that it is undesirable to end up in a situation where the driver steers faster than the steering rack is able to move. To mitigate such a situation, additional high damping is proposed to make it harder for the driver to further increase the speed.

The damping coefficient, i.e. the gain from angular velocity to damping torque in the hand wheel was constructed in a way to cope with extra damping required at zero steering wheel position and to prevent overshoot when releasing the hand wheel. The coefficient was constructed as,

$$T_{damping} = (c_1 + (c_2 + c_3 v_x) e^{-b_1 \varphi_{hw}^2} +) \dot{\varphi}_{hw} + c_4 \dot{\varphi}_{hw}^2,$$

where the coefficients $c_1, c_2, c_3$ are tuned for normal operation and the last coefficient is tuned for extreme angular rotations, to mitigate hand wheel to road wheel discrepancy for large hand wheel angle rates.

**Drifting** is a special case where the steering feel is radically altered. In the situation when only the rear axle's lateral tire forces are exhausted and there is a substantial sliding occurring the angle where the zero torque occurs is shifted.

Besides the non-trivial task of estimating this body slip angle, the haptic torque feedback of the hand wheel can be simply shifted in angle accordingly in the present algorithm to accommodate the sensation. s

### 3.2 Variable steering ratio

With a constant steering ratio on conventional steering systems, a compromise must be reached among several competing factors. For instance, a more direct ratio will enhance responsiveness and facilitate maneuverability of the vehicle. However, an excessively direct ratio will make the car overly responsive and nervous at higher speeds. Furthermore, the more direct the ratio, the less a given driver torque will contribute to steering the vehicle, increasing reliance on steering assist.

**Vehicle speed dependency** When it comes to designing the variable steering ratio, many strategies can be considered to achieve any desired steering ratio. One of these, as indicated by the preceding discussion, the steering ratio could be adjusted based on the vehicle's speed. A more direct steering ratio would be employed at lower speeds, gradually transitioning to a less direct ratio as the speed increases.

To simplify the discussion, a neutral steered vehicle can be considered. In this case, the following relationships between the front steering angle ($\delta$) and curvature ($\kappa$), yaw rate ($\dot{\psi}$) and lateral acceleration ($a_y$) hold for steady state motion[11]:

- curvature gain: $\kappa/\delta = 1/L$
- yaw rate gain: $\dot{\psi}/\delta = v_x/L$
- lateral acceleration gain: $a_y/\delta = v_x^2/L$

For a fixed steering angle and varying speed, three ratio strategies can be identified:

- Constant curvature - constant steering ratio
- Constant yaw rate - ratio changes linearly with vehicle speed
- Constant lateral acceleration - ratio changes proportionally to the vehicle speed squared.

When designing country roads the maximum curvature is generally determined by the design speed of the curve [6]. Therefore the constant lateral acceleration approach would allow for a large variation in steering ratio with a constancy to the road design.

To allow for even larger changes the ratio $n$ a quadratic and quartic ($p = 2, 4$) relationship between ratio and vehicle speed $v$ were tested.

$$n = \begin{cases} k(v - v_{\text{lim}})^p + n_{\text{lim}}, & \text{if } v < v_{\text{lim}}. \\ n_{\text{lim}}, & \text{otherwise.} \end{cases}$$

with $n_{\text{lim}}$ being the steer ratio at vehicle speed $v = v_{\text{lim}}$ and where

$$k = (n_0 - n_{\text{lim}})/v_{\text{lim}}^p$$

The ratio used further on in the paper is defined as a factor acting on a normal ratio for the test vehicle. A higher value indicate less angle of the hand wheel to move the road wheel.

**Steering wheel angle dependency** In [10] it is proposed to have a hand wheel end-stop at a fixed angle, independent of the vehicle speed, e.g. at $\pm 150^o$. If a speed variable ratio as presented above would be combined with this end-stop strategy, the full range of rack travel could not be utilized as the speed increases. To always be able to reach the road wheel angle limit for a fixed steering wheel angle range, a quadratic or cubic relationship between the steering ratio and steering wheel angle could be employed. For example,

$$\delta = \frac{1}{n}\delta_H + \frac{\delta_{\max} - \delta_{H,\max}/n}{\delta_{H,\max}^3}\delta_H^3$$

where $n$ is the vehicle speed dependent ratio, $\delta_H$ is the steering wheel angle and $\delta$ is the (average) road wheel angle.

## 4 Results

The results are divided as in the previous section, where the proposed approaches are applied to the test vehicle.

### 4.1 Haptic feedback torque

The base torque with its tuning parameters were fitted to measurement of a vehicle with a conventional steering system. The outcome of this tuning, shown to the left in figure 3, illustrate the performance of the proposed scheme for different speeds. Worth noticing is that there is a lack of measurement data for the case of higher tire force utilization's when the aligning torque drops. Once can also see a software implementation of an end-stop at roughly 9 radians.

To illustrate the performance in general driving, two laps on a closed circuit test track was performed, one with the conventional steering system and one with the SbW system. The hand wheel angles were recorded and compared in the bottom subplot to the right in figure 3. The upper subplot in the figure shows the resemblance between the two test runs for the hand wheel torque.

### 4.2 Variable ratio

The approach while testing the function involved changing one parameter in equation and equation at the time while documenting the process. The initial

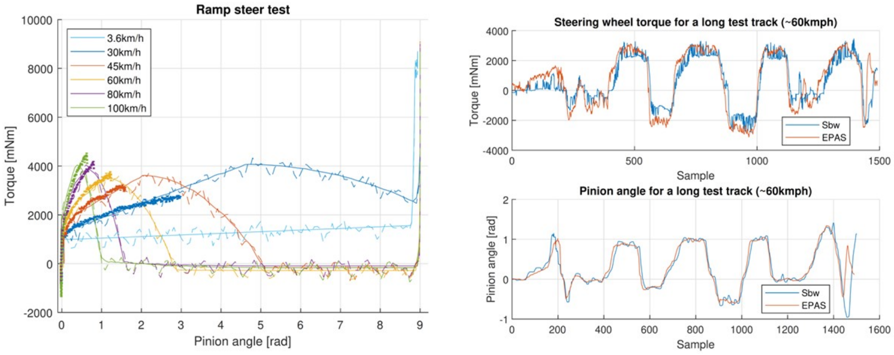

**Fig. 3.** **Left**: Ramp steer test data from EPAS car along with the algorithms described in the previous section. **Right**:A closed circuit test track ran once with the EPAS and once with the steer-by-wire arrangement

parameters, which served as a baseline for the experimental process, were defined such that the initial (zero speed) gain factor was five times more direct than the high speed ratio and then quadratically transitioning to the standard ratio by 50 km/h.

The vehicle was observed to be highly manoeuvred at lower speeds, while maintaining stability at higher speeds. However, it was observed that while driving at speeds between 40 km/h and 60 km/h, a higher gain factor could be used to ensure more mobility.

Another test was conducted where the zero speed (direct) to high speed (indirect) ratio was was changed to 6:1 while also moving the threshold $v_{\mathrm{lim}}$ to 100 km/h. This solution provides more mobility while driving at speeds between 40 km/h and 60 km/h than the previous attempt. On the other hand, since the gain factor is less than one, the vehicle was observed to be more difficult to manoeuvre at higher speeds, more exactly speeds above 80 km/h. When the function is to the power of four it provides more stability rather than mobility compared to when the function is to the power of two. When driving at speeds above 80 km/h, the vehicle was less responsive, and the driver was required to turn the hand wheel more than what was wanted. This effect was most noticeable whenever the driver needed to do a sharp turn. Although the vehicle acquired more mobility at higher speeds, it also decreases the stability at mid-range speeds.

An additional test was conducted where the direct to indirect ratio was set to 4:1. This combination was observed to give the vehicle stability for mid-range speeds as well as higher speeds. This was the case for the function to the power two and to the power of four. Although the vehicle was stable at higher and mid-range speeds, it did not provide enough mobility at lower speeds. The vehicle was observed to be more difficult to manoeuvre compared to a maximum ratio of five or six. The mobility was increased by moving the threshold, but this only affects the mobility and stability at higher speeds.

This combination of a direct to indirect ratio of 5:1 gave the vehicle enough mobility at lower speeds while maintaining good stability even at higher speeds. The threshold was moved between 150 km/h and 50 km/h, and it was observed that a threshold at 150 km/h made the vehicle insufficiently stable at higher speeds while a threshold at 50 km/h forced the driver to turn the steering wheel more than wanted. It was also observed that the function to the power of four was more versatile because the change in ratio while accelerating were more natural compared to when the function was to the power of two. Figure 4.right shows the finalized function.

Example of steering wheel angle dependent ratio to always reach the end of rack travel (maximum road wheel angle) is shown in Figure 4.left. The dashed line in the figure indicates the road wheel angle that is reached for a ratio that is not steering wheel angle dependent. The numerical values are for illustration only.

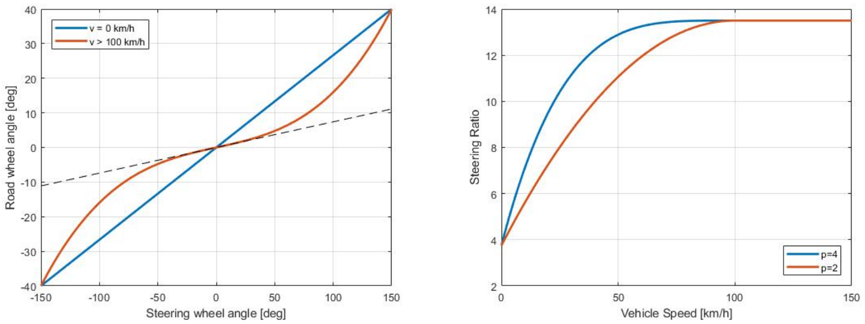

**Fig. 4.** Left:Example of steering wheel angle dependent ratio to always reach the end of rack travel. Right: Steer ratio as function of speed

## 5 Discussion

The initial tests showed that a good steering feel could be achieved with the proposed simple expressions. Simplicity of the expressions pave ease and robustness of implementation in real hardware. The design points of the expression are different model based approaches, but is still fairly intuitive to be tuned at the test track. The more extreme driving consequences (front/rear axle drifting) was not tested fully due to constraints on the test track.

The inferior tracking performance of the steering rack position on the prototype vehicle made the problem of poor synchronization of the driver intention with the hand wheel and poor response of the road wheel palpable. The need for a feature to mitigate that the driver input is hard to track for the rack is obvious. Even though the strategy of extra damping in these situations was tested to some extent with positive response, it could not fully be tested due to constraints on the test track used.

The final speed dependent and the final speed and position dependent solutions are perceived quite similar by drivers. An inexperienced driver might not even notice any difference between them because both start at about the same ratio and ends up at the standard steering ratio when the speed is 100 km/h. The situation is different in higher speeds, because in the speed and position dependent implementation there is a steeper slope towards the end-stop. This might be problematic and even unsafe. For example, if a driver drastically turns the steering wheel at high speed, the reaction of the car might not be the intended by the driver with very high road wheel angles.

One might ask how important it is to reach the rack end stop at high speeds? This is a question that people feel different about. Some do not want to limit the steering in any situations, and some do not feel the need to be able to steer to end lock at high speed. It is quite uncommon for a passenger car to steer close to end lock at high speed if driving on roads. One situation it might be needed is if the vehicle swerving and loses the grip of the road, then the driver might want to compensate by steering the opposite direction and use the wheel´s full range. A test like this was not made, and it is hence difficult to evaluate. However, while driving on the test track in high speed and rounding a bend it did still feel stable and comfortable.

The combination of variable steering ratio and the haptic feedback torque was not fully tested on the test track. Simple tests like changing speed (acceleration/braking) in a curve was tested that assess both the haptics and the ratio. Further testing of this needed to fully assess and evaluate how perception of the haptics is influencing perception of the ratio and visa versa. One thing that was observed was an excessive vehicle response when maneuvering in low speed and releasing or moving the hand wheel back to zero position. This suggest that the haptics needs to be adjusted to the steering ratio.

## 6 Conclusions

A simple data driven haptic feedback torque strategy for steer-by-wire has successfully been proposed and implemented in a test vehicle. Initial tests suggest that, despite its simplicity, seems to generate a sensation that one expect from a conventional steering system. From a haptics perspective, some fundamental pieces are still missing, such as tire-to-road friction influence to capture the sensation of driving on different road conditions.

Various aspects of how a speed dependent ratio could be created and implemented in a real vehicle has been examined. There are endless ways to create a variable steering ratio for steer-by-wire and only a few has been tested for this project. From the tests that have been conducted some conclusions can been drawn. Both the speed variable ratio and the speed and position variable ratio has good stability and mobility with a maximum direct to indirect ratio of around 5:1 at 0 km/h compared to the indirect ratio above 100 km/h. These functions have only been tested on test tracks, to be able to evaluate the implementations in all kinds of driving situations more tests, including those on public roads, must be done. These initial tests suggest that the simple strategies show promise.

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