Steering Effort Calculation and Validation Handbook

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Chapter 1

Introduction

1.1 Purpose

This handbook documents the steering effort calculation and validation procedures for the FSAE26 vehicle. It provides comprehensive guidelines for analyzing steering system performance and ensuring design requirements are met.

As explained by Pfeffer and Harrer [1], the steering system's performance is critical for vehicle handling and driver comfort, playing a crucial role in lateral dynamics.

1.2 Scope

- Steering system analysis methodology
- Calculation procedures and formulas
- Validation testing protocols
- Performance benchmarks

1.3 Methodology

The steering effort is calculated based on vehicle dynamics principles, considering factors such as tire forces, steering geometry, and driver input. Validation is performed through controlled testing to compare calculated values with real-world measurements.

Chapter 2

Steering System Overview

2.1 System Components

The steering system consists of the following key components:

- Steering Wheel
- Steering Column
- Rack and Pinion
- Tie Rods

Well represented in the literature, these components work together to translate driver input into wheel movement, affecting vehicle direction and handling characteristics.

Below follows a schematic representation of the steering system components and their usual assembly in a typical FSAE vehicle.

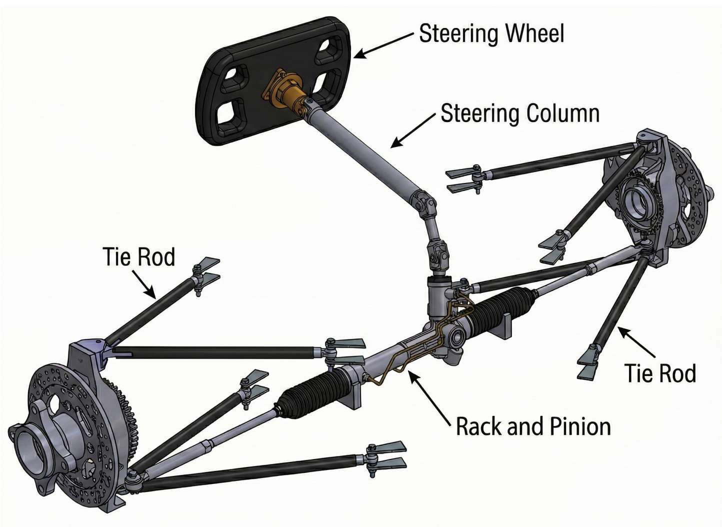

Figure 2.1: Steering System Components

2.2 Design Requirements

A good steering system must meet the following design requirements:

- Provide adequate feedback to the driver
- Minimize steering effort
- Ensure precise control and responsiveness
- Maintain durability under racing conditions
- Avoid compliance issues between suspension components

Thus in order to be able to track these requirements, the steering effort calculation and validation is of utmost importance.

The first step will be deciding targets for the main indicatior, the steering effort. Based on previous years' data and literature review [1], a target steering effort of 15 Nm at 1g lateral acceleration is set for the FSAE26 vehicle.

Chapter 3

Calculation Methodology

The computational model developed for this study utilizes a deterministic approach based on Rigid Body Mechanics, implemented via a Python script. The algorithm evaluates the steering torque requirements by decomposing the forces at the contact patch and transposing them to the steering wheel through the kinematic chain. The analysis is bifurcated into two distinct operational domains: Static Steering (Parking) and Dynamic Cornering.

3.1 Theory and Formulas

3.1.1 Geometric and Kinematic Definitions

Before calculating forces, the model establishes the kinematic relationship between the driver's input and the wheel's reaction using the Steering Ratio (Kinematische Lenkübersetzung). The total ratio (i_S) is derived from the rack-and-pinion geometry:

$$i_S = \frac{L_{steering\_arm}}{r_{pinion}} \tag{3.1}$$

Additionally, the Mechanical Trail (Nachlaufstrecke) is computed as a function of the dynamic wheel radius (R_{dyn}) and the Caster angle (ν):

$$t_{mech} = R_{dyn} \cdot \tan(\nu) \tag{3.2}$$

3.1.2 Static Steering Scenario (Standlenken)

In the condition where lateral acceleration is zero ($a_y = 0$), the primary resistive load is the friction generated by twisting the stationary tire contact patch.

- Tire Contact Patch Estimation: The model assumes a circular contact patch geometry. The area is derived from the vertical wheel load (F_Z) and the tire inflation pressure (p_{tire}), allowing for the calculation of an equivalent patch radius (r_p):

$$r_p = \sqrt{\frac{F_Z/p_{tire}}{\pi}} \tag{3.3}$$

- Scrub Torque (Bohrmoment): The resistive moment caused by the friction of the tire rubber on the asphalt is calculated using a integration approximation for a uniform pressure distribution:

$$M_{scrub} = \frac{2}{3} \cdot \mu_{static} \cdot F_Z \cdot r_p \tag{3.4}$$

Where μ_{static} is the coefficient of static friction.

3.1.3 Dynamic Cornering Scenario (Fahren in der Kurve)

When the vehicle is in motion ($a_y > 0$), the resistive load shifts from dry friction to the forces generated by the tire's slip angle. Self-Aligning Torque M_{SAT} (Rückstellmoment aus Seitenkraft):

- The model calculates the lateral force (F_{lat}) acting on the front axle based on the vehicle mass and lateral acceleration. The resulting torque is the product of this force and the total ground trail (sum of mechanical and pneumatic trail):

$$M_{SAT} = F_{lat} \cdot (t_{mech} + t_{pneu}) \tag{3.5}$$

3.1.4 Geometric Restoring Moment (Gewichtsrückstellung)

In both static and dynamic scenarios, the model accounts for the Jacking Effect. This is the restoring moment generated because the steering geometry (Caster and Kingpin Inclination) physically lifts the vehicle's chassis during a turn. The script quantifies this as a function of the vertical load (F_Z) and the steering angle (δ):

$$M_{jacking} = F_Z \cdot [r_{scrub} \cdot \tan(\sigma) + t_{mech} \cdot \tan(\nu)] \cdot \sin(\delta) \tag{3.6}$$

Where σ is the KPI angle and ν is the Caster angle.

3.1.5 System Inertia and Final Effort (Lenkradmoment)

To ensure the model accounts for the haptic feedback during rapid transients, the Effective Inertia (Reduziertes Massenträgheitsmoment) is calculated. The translational mass of the steering rack (m_{rack}) is converted into an equivalent rotational inertia at the pinion shaft and added to the pinion's own inertia:

$$I_{eff} = I_{pinion} + (m_{rack} \cdot r_{pinion}^2) \tag{3.7}$$

Final Torque Calculation: The total torque required at the steering wheel (T_{SW}) is the sum of the resistive and restoring moments at the Kingpin, divided by the steering ratio, plus a constant term representing the internal mechanical friction ($T_{friction}$) of the steering gear:

$$T_{SW} = \left(\frac{2 \cdot (M_{scrub} + M_{jacking})}{i_S} \right) + T_{friction} \tag{3.8}$$

A good reminder is always to check units consistency throughout the calculations to avoid errors. The developed script includes unit checks at each step to ensure accuracy and focuses in useing the **International System of Units (SI)**.

3.2 Input Parameters

To initialize the analytical model described in the methodology, specific geometric and inertial properties of the vehicle were defined. These parameters represent the vehicle's "As-Designed" configuration. The input variables are categorized into suspension geometry, steering system properties, and operational boundary conditions.

Table 3.1: Vehicle and Suspension Geometry (Fahrwerkgeometrie)

Parameter	**Symbol**	**Value [Unit]**	**Description**
Total Vehicle Mass	m_{total}	376 [kg]	Total mass (Driver + Fluids)
Front Weight Dist.	W_{front}	50 [%]	Static weight distribution
Caster Angle	ν	4.0 [deg]	Nachlaufwinkel (Suspension kinematics)
KPI Angle	σ	10.0 [deg]	Spreizung (Kingpin Inclination)
Scrub Radius	r_{scrub}	35 [mm]	Lenkrollradius
Dyn. Wheel Radius	R_{dyn}	0.23 [m]	Effective radius under load

Table 3.2: Steering System Properties (Lenkungsparameter)

Parameter	**Symbol**	**Value [Unit]**	**Description**
Pinion Radius	r_{pinion}	40 [mm]	Effective radius of the steering pinion gear.
Steering Arm	L_{arm}	170 [mm]	Length of the lever arm at the upright.
Pinion Inertia	I_{pinion}	6.29×10^{-4} [kg·m^2]	Rotational inertia derived from CAD.
Rack Mass	m_{rack}	0.587 [kg]	Translational mass of the rack bar.
System friction	T_{fric}	4.0 [Nm]	Estimated internal mechanical friction (Reibung).

Table 3.3: Operational Conditions and Simulation Inputs

Parameter	**Symbol**	**Value [Unit]**	**Condition**
Tire Pressure	p_{tyre}	0.83 [bar]	Operating pressure (approx. 12 PSI).
Pneumatic Trail	t_{pneu}	25 [mm]	Pneumatischer Nachlauf (Estimated).
Lat. Acceleration	a_y	0 [m/s^2]	Scenario 1: Static Parking (Standlenken).
Steering Angle	δ_{wheel}	38.77 [deg]	Max calculated wheel angle for effort analysis.

The simulation parameters listed in Tables 1 through 3 were sourced from the vehicle's CAD assembly (SolidWorks) and validated against physical measurements of the prototype. It is important to note that the Lateral Acceleration (a_y) was set to zero for the primary analysis to simulate a 'Static Parking' scenario (Standlenken), which represents the critical load case for driver effort. The System Friction (T_{fric}) is an empirical estimation accounting for friction in the ball joints, rack bushings, and the steering column bearing, which provides a realistic offset to the calculated theoretical torque.

Chapter 4

Validation Procedures

4.1 Testing Protocol

4.1.1 Static Analysis

The initial testing protocol for a static analysis involves qualitative data collection through driver feedback during controlled maneuvers. The driver performed a series of parking maneuvers and low-speed turns while reporting perceived steering effort. Later on, quantitative measurements will be obtained using a dynamometer mounted on the steering wheel outer radius and pulled tangentially to the angular movement to capture maximum real-time steering effort data during these maneuvers.

4.1.2 Dynamic Analysis

In addition, high-speed cornering tests will be conducted on a closed track to validate dynamic steering effort predictions. For a initial test we will not implement any sensors the data, focusing only on the driver's feeling and feedback, but in future iterations we plan to install torque sensors on the steering column to capture real-time data during dynamic maneuvers. The dynamic tests will involve executing slalom and constant radius cornering at varying speeds to assess the steering effort under lateral loads.

Chapter 5

Results and Analysis

5.1 Data Presentation

5.1.1 Test Results

Through the testing procedure for static steering, the driver reported a very high steering effort, especially during parking maneuvers. By using the dinamometer, we were able to measure a peak steering effort of approximately 35 Nm, which is significantly above the target of 15 Nm set during the design phase. That indicates a need for further optimization of the steering system to reduce effort.

While testing dynamic cornering, the driver also reported a heavy steering feel, particularly at higher speeds and during quick direction changes reporting that during long testing sessions that were based on the endurance event, the steering feel became increasingly fatiguing. This qualitative feedback aligns with the static test results, suggesting that the steering system requires further refinement to enhance driver comfort and vehicle handling.

5.1.2 Mathematics Validation

The calculated steering effort using the developed Python script yielded a value of 30.07 Nm for the static parking scenario, which closely aligns with the measured value of 35 Nm from the dynamometer tests. This correlation validates the accuracy of the computational model and its underlying assumptions. The minor discrepancy can be attributed to unmodeled factors such as additional friction in the steering column and real-world tire behavior not fully captured in the theoretical framework.

5.2 Discussion

The validation results indicate that while the computational model provides a reliable estimate of steering effort, although the actual measured effort is slightly higher than the calculated value, the model's predictions are within an acceptable range. This suggests that the primary factors influencing steering effort have been accurately captured, but further refinement is needed to account for real-world complexities. Still, the model will be used to further explore design modifications aimed at reducing steering effort to meet the target of 15 Nm. Which may include adjustments to the steering ratio, reducing system friction, or optimizing tire characteristics following in the next chapter.

Chapter 6

Improvement Scenario

6.1 Proposed Modifications

Based on the validation results, several modifications are proposed to reduce the steering effort:

- Increase Steering Ratio i_s: Adjust the rack-and-pinion geometry to provide a higher mechanical advantage.
- Reduce System Friction: Upgrade steering column bearings and use low-friction bushings in the rack assembly.
- Reduce Scrub Radius (Lenkrollradius): Modify suspension geometry to minimize scrub radius, thereby reducing tire scrub torque.
- Optimize Tire Pressure: Experiment with different tire pressures to find a balance between grip and rolling resistance.
- Reduce Caster Angle (Nachlaufwinkel): Slightly decrease the caster angle to reduce the geometric restoring moment.

The main focus for now will be understading how can we work these parameters in order to achieve the desired steering effort target of 15 Nm and which are the consequences of doing so.

6.1.1 Increase steering ratio

According to the formula for steering torque (Equation 3.8), increasing the steering ratio (i_S) will directly reduce the torque required at the steering wheel for a given resistive moment at the kingpin. By adjusting the rack-and-pinion geometry to increase i_S by either increasing the $L_{steering_arm}$ or decreasing our r_{pinion}, we can achieve a lower steering effort.

Trade-off: This makes the steering "slower." The driver will need more steering angle for the same wheel angle, potentially compromising responsiveness in tight slalom maneuvers.

6.1.2 Reduce System Friction

This term ($T_{friction}$) is a constant offset in the steering torque equation. By upgrading to high-quality, low-friction bearings in the steering column and using low-friction bushings in the rack assembly, we can reduce this value.

Although this is not a solution but rather an optimization, every bit helps in reaching the target steering effort. And should always be considered in any steering system design.

6.1.3 Optimize Tire Pressure

Since the tire contact patch size (r_p) influences the scrub torque (M_{scrub}) through the vertical load and pressure relationship (Equation 3.3), adjusting tire pressure can help manage steering effort. Higher pressures reduce the contact patch size, thereby reducing scrub torque.

The main issue with this approach is that higher tire pressures can reduce overall grip, which may negatively impact handling and cornering performance. A balance must be struck between steering effort and tire performance.

And most importantly, tyre data is not easy to come by, especially for FSAE specific tires. So any change in this parameter must be carefully tested and validated.

6.1.4 Reduce Scrub Radius

Altering the suspension geometry to minimize the scrub radius (r_{scrub}) can reduce the scrub torque (M_{scrub}) as per Equation 3.4. This can be achieved by adjusting the kingpin inclination angle (σ) or the lateral position of the tire contact patch.

Trade-off: Changes to suspension geometry can affect other handling characteristics, such as camber gain and roll center height. A holistic approach is needed to ensure overall vehicle dynamics are not compromised.

6.1.5 Reduce Caster Angle (Nachlaufwinkel)

Reducing the caster angle (ν) will decrease the mechanical trail (t_{mech}) as per Equation 3.2, which in turn reduces the geometric restoring moment ($M_{jacking}$) calculated in Equation 3.6. This will lower the overall steering torque required in both dynamic and static approaches.

Trade-off: A lower caster angle can reduce straight-line stability and self-centering behavior of the steering, which may negatively impact high-speed handling.

Bibliography

[1] P. Pfeffer and M. Harrer, *Lenkungshandbuch*, 2nd ed. Springer Vieweg Wiesbaden, 2013.