Traction Control System

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1 Project Motivation

Vehicles have been used for transportation since the dawn of the Industrial Revolution. Over time, advancements have also focused on ensuring safety during travel, regardless of weather conditions. However, harsh weather such as rain or snow can cause tires to slip, leading to accidents or even fatalities.

Regardless of the engine's power, the tires are responsible for generating the force required to move the vehicle forward. If the tires slip on the road, traction is lost, and the car cannot move as expected. This issue arises when the tires fail to grip the surface adequately, reducing the traction force needed to propel the vehicle.

To address this problem, several techniques have been developed recently to control tire slippage (also known as slip ratio), ensuring a safer and more controllable driving experience. One such solution is the Traction Control System (TCS), which is designed to prevent tire slipping. The TCS works by maintaining the wheel speed as close as possible to the vehicle's speed, ensuring that maximum tractive force is generated at all times. This improves safety and driving stability, particularly in challenging conditions.

2 Possible Solution

The most common and straightforward way to control torque and maintain the required slip ratio is by using a PID controller. A PID, or Proportional-Integral-Derivative controller, is provided with an error function, which is the difference between the desired and actual slip ratio (or wheel speed). Based on this error, the controller outputs a controlled torque that is applied to the drivetrain or wheels.

The PID controller works according to the equation:

$$\text{Torque} = K_p \cdot \text{error}(t) + K_i \cdot \int_0^t \text{error}(\tau)\, d\tau + K_d \cdot \frac{d(\text{error}(t))}{dt}$$

Here:

- K_p, K_i, and K_d are the proportional, integral, and derivative gain constants, respectively.
- These constants need to be tuned based on the system's requirements.

When slip occurs (i.e., when the vehicle speed does not match the wheel speed), the PID control algorithm adjusts the torque to maintain an optimal difference between the wheel speed and the vehicle speed. This helps maximize traction force and prevents slipping.

While simple PID controllers are effective, they are often not responsive enough in critical situations where faster response times are necessary. Additionally, tuning the PID gains becomes challenging when road conditions change.

3 Literature review (Case Studies on Control Strategies for Traction and Speed Control)

1. Fuzzy-Based PID Controller for Speed Control of D.C. Motor

- A simple D.C. motor's speed is controlled using a PID + Fuzzy control system.
- The error between the desired and actual wheel speed is fed into the controller.
- The controller processes the error to provide a controlled voltage to the motor.
- Though not directly related to traction control, it demonstrates combining fuzzy inference logic with a PID controller to produce controlled torque or voltage.

2. Traction Control System Using a Fuzzy Representation of the Vehicle Model

- A robust control strategy is proposed using a fuzzy state feedback controller.
- The controller is based on Takagi-Sugeno (TS) fuzzy representation of vehicle dynamics, drivetrain, and wheel motion.
- A non-linear control strategy is used with state-space representation.
- Stability is ensured using Lyapunov's and H_∞ approaches.

3. Development of Traction Control System and Wheel Slip Control

- Torque is controlled via a throttle valve mechanism.
- This approach is specific to internal combustion engines.
- Requires detailed study for each car type, making implementation exhaustive.

4. Traction Control Algorithm Based on Fuzzy PID and PWM Modulation

- Combines fuzzy PID control strategy with PWM modulation for braking.
- Error and derivative of error between wheel speed and actual speed are fed into the fuzzy inference system.
- Real-time calculation of PID gains produces controlled throttle and braking pressure.
- Two fuzzy PID controllers work simultaneously for acceleration and deceleration.
- Dual control can lead to vehicle instability.

5. Study on Optimal Slip Ratio Identification and Traction Control for Electric Vehicles

- Slip ratio is determined in real time using a recursive least square algorithm with a forgetting factor.
- Adhesion coefficient is calculated using a PI integrator and fuzzy inference categorizes road conditions.
- A PID controller uses the desired slip ratio to control the electric motor's torque.

- Robust system adapts to varying road conditions, but tuning PID gains is complex and time-consuming.

Understanding and Chosen Control System

- Various studies have highlighted control strategies for managing torque and braking pressure to handle slipping.
- Most papers use a PID controller as a key component but face challenges in determining optimal PID gains and slip ratios.
- Fuzzy logic enhances PID control by dynamically adjusting gains based on real-time errors, making it robust against varying conditions.
- In this project, we propose a PID controller with fuzzy inference logic to adjust PID gains in real time based on the error between the actual and desired slip ratio.
- This approach provides controlled torque, ensuring vehicle stability and safety under different conditions.

4 Equation

Traction and Slip Ratio Overview

- **Ideal Condition**: Vehicle tires stick perfectly to the road via the contact patch, and the rubber's elasticity provides the traction force necessary for forward motion.
- **Slippery Condition**: The driven tires may not fully adhere to the road, causing them to rotate at a speed different from the vehicle's velocity.
- **Slip Ratio ()**: Measures the difference between the driven wheel's angular velocity ($\theta\omega$) and free-rolling velocity (ω_0):

  $$k = \frac{\theta\omega - \omega_0}{\omega_0}, \quad \omega_0 = \frac{x}{R_L}$$

  where:

  - x: Vehicle velocity
  - R_L: Radius of the loaded rear tires (RWD vehicle)

Equations of Motion with Slip Ratio

1. **Vehicle Acceleration**:

$$(m + m_{EQFT})\ddot{x} = F_{XR}(k) - f_r mg - 0.5\rho C_D A x^2$$

where:

- m: Vehicle + driver mass
- m_{EQFT}: Equivalent front train mass
- $F_{XR}(k)$: Tractive force as a function of slip ratio
- f_r: Rolling resistance coefficient
- ρ: Air density, C_D: Drag coefficient, A: Frontal area

2. **Wheel Angular Acceleration**:

$$I_{DT}\ddot{\theta}\omega_R = F_{XR}(k)R_{TR} - G_{RAX}G_{RTRAN}T_e$$

where:

- I_{DT}: Mass moment of inertia of the drivetrain
- R_{TR}: Loaded tire radius
- G_{RAX}, G_{RTRAN}: Gear ratios for axle and transmission
- T_e: Engine torque

Note

- **Optimal Slip Ratio** (k): For any road condition, k (typically around 0.2) maximizes tractive force.
- **Control Objective**: The vehicle's wheels must maintain an optimal slip ratio to ensure maximum traction and prevent slip, which varies with road conditions. We will compare the performance of a conventional PID controller and a fuzzy PID controller in controlling the input torque to achieve this optimal slip ratio.

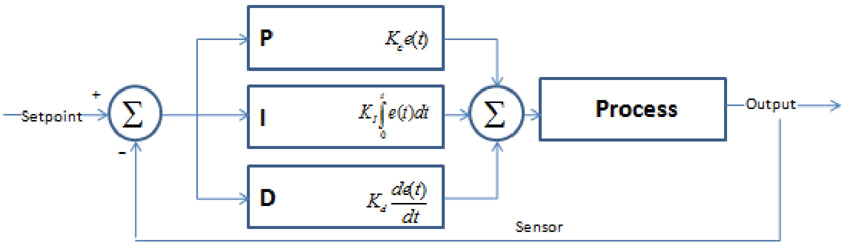

Figure 1: PID Controller using Negative Feedback Structure

5 Method

5.1 PID Controller

A PID controller, as described earlier, generates a controlled output based on the error function. In a traction control system, the controlled output is the torque fed to the vehicle's engine, based on the error between the desired slip ratio and the current slip ratio.

The error-driven torque is calculated using the following equation:

$$\text{Torque} = K_p \times \text{error}(t) + K_i \times \int \text{error}(t)\,dt + K_d \times \frac{\text{derror}(t)}{dt} \tag{1}$$

Here, K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. These gains adjust the torque to bring the slip ratio closer to the desired value over time.

5.2 Fuzzy PID Controller

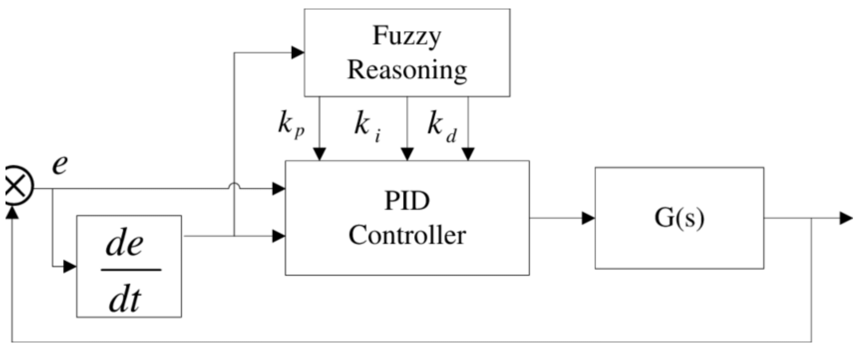

Figure 2: PID Controller using Negative Feedback Structure

Fuzzy logic is a method that emulates human deductive thinking, allowing the incorporation of human expertise and experience into building a controller. Unlike binary logic, fuzzy logic deals with degrees of truth. In this project, fuzzy logic is used to self-tune the K_p, K_i, and K_d gain values based on the error function and the derivative of the error function in real-time.

For this project, we have set $K_d = 0$ since the response is aperiodic. Seven fuzzy membership functions, which are triangular in shape, were defined for both the input (error and derivative of error) and output (the gains K_p and K_i).

The fuzzy rules are as follows:

- When the error is large, K_p is large and K_i is small, which increases the controlled torque rapidly at the beginning.
- As the error decreases and the integral of the error increases, K_p reduces and K_i increases. This ensures that the integral gain plays a major role in keeping the controlled torque at the optimal value to maintain the desired slip ratio.

6 Experimental Setup

In this project, a 2019 Corvette ZR1 (RWD) car operating in its 1st gear was used to simulate the performance of the controllers under slippery conditions. Initially, a slip ratio (k) of 0.01 and 0.15 was introduced at the start of the simulation, and the performance of the PID and Fuzzy-PID controllers was compared.

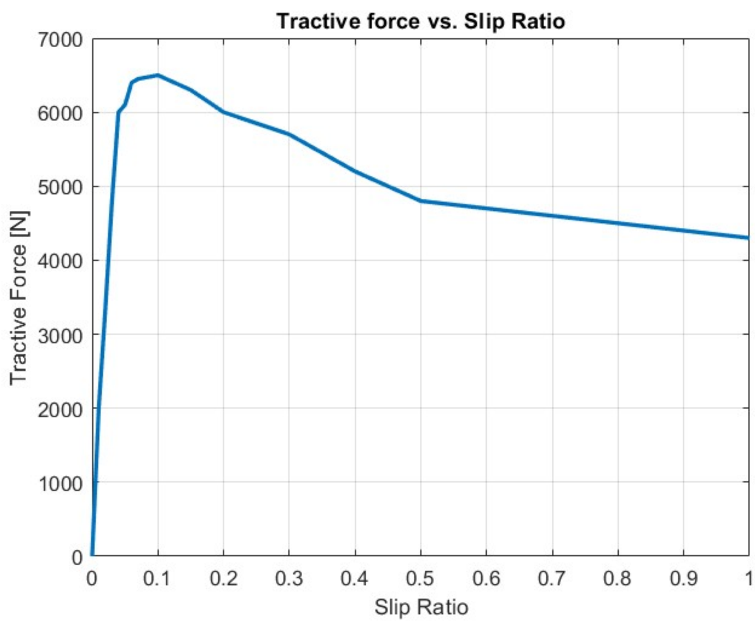

Figure 3: Tractive Force vs. Slip Ratio Curve

In Figure 3, the graph showing the relationship between tractive force and slip ratio is presented. From the figure, it can be seen that the optimal slip ratio occurs at $k = 0.1$. The car was given a rolling start of 5 mph. To evaluate and compare the performance of both controllers, the following metrics were considered: settling time, rise time, percentage overshoot, and mean square error.

Additionally, the maximum achievable torque (controlled output of the PID controller) is 850 N·m, as specified in the car's specification charts.

7 Results

For the conventional PID controller, the proportional, integral, and derivative gain values were set to $K_p = 8000$, $K_i = 7550$, and $K_d = 0$ using a trial-and-error method.

As shown in Figure, the Fuzzy-PID controller performs better than the conventional PID controller. The Fuzzy-PID controller achieves better rise time and settling time for both initial slip ratios ($k = 0.01$ and $k = 0.15$).

- For an initial slip ratio of $k = 0.01$, the settling times for the Fuzzy-PID and PID controllers are 0.21 sec and 2.9 sec, respectively. The mean square errors are 1.0636×10^{-4} for Fuzzy-PID and 1.0090×10^{-4} for PID.
- For an initial slip ratio of $k = 0.15$, the settling times for Fuzzy-PID and PID are 0.22 sec and 2.85 sec, respectively. However, the Fuzzy-PID controller exhibits a higher percentage overshoot, which may lead to undesirable side effects. The mean square errors for Fuzzy-PID and PID are 1.0758×10^{-4} and 1.0051×10^{-4}, respectively.

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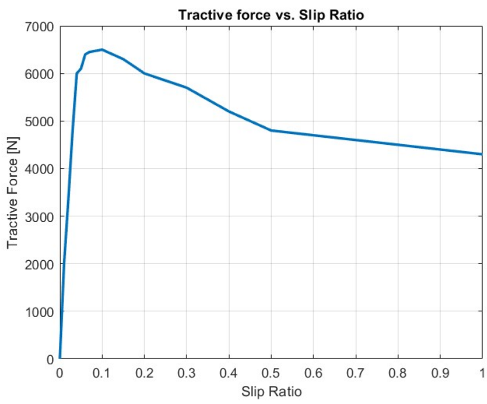
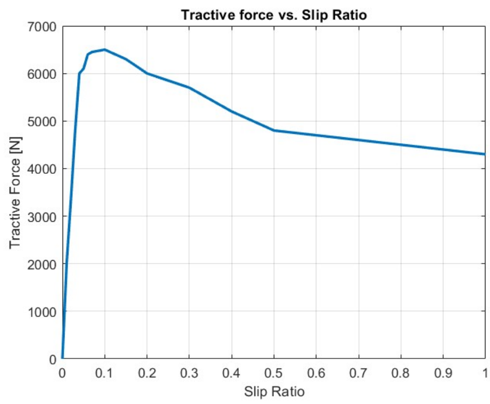
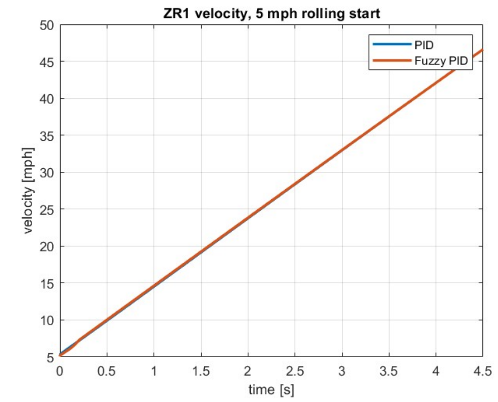
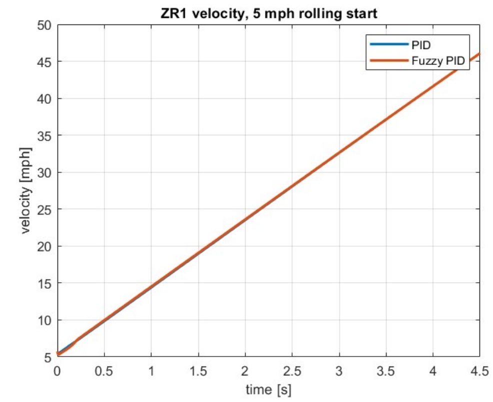





ZR1 velocity, 5 mph rolling start
velocity [mph]
time [s]
PID
Fuzzy PID


ZR1 velocity, 5 mph rolling start
velocity [mph]
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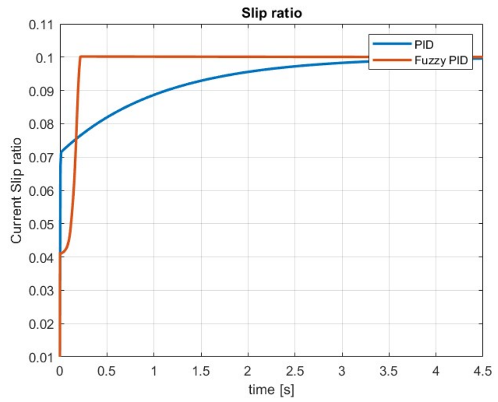
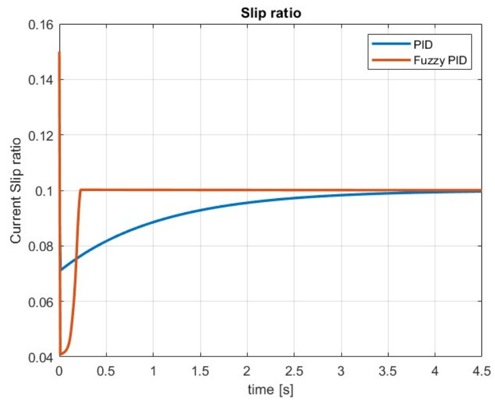
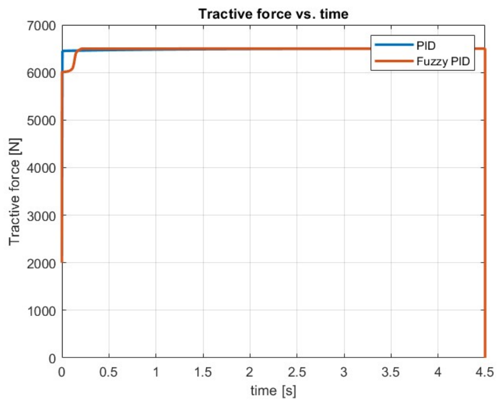
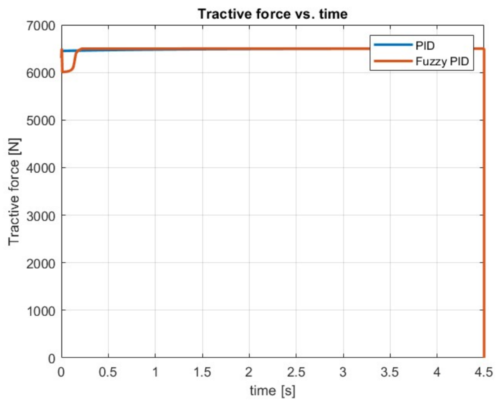
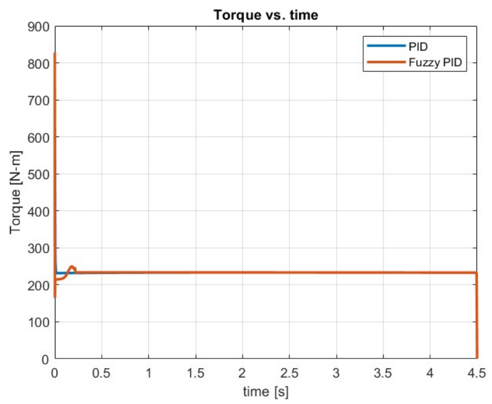
PID
Fuzzy PID

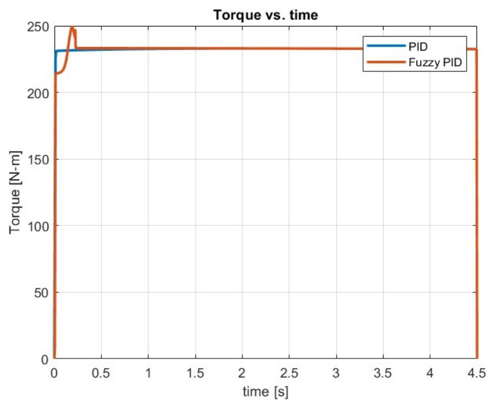

Slip ratio
Current Slip ratio
time [s]
PID
Fuzzy PID

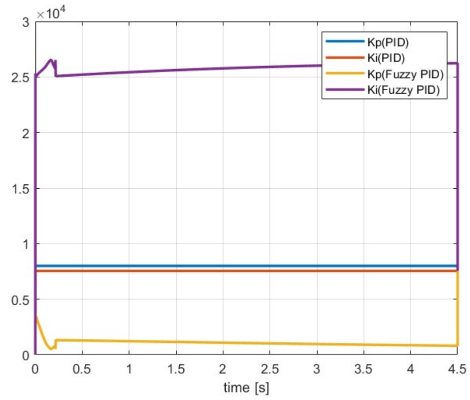

Slip ratio
Current Slip ratio
time [s]
PID
Fuzzy PID

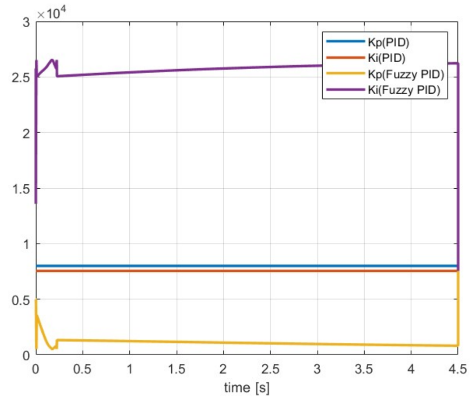

Tractive force vs. time
Tractive force [N]
time [s]
PID
Fuzzy PID


Tractive force vs. time
Tractive force [N]
time [s]
PID
Fuzzy PID


Torque vs. time
Torque [N-m]
time [s]
PID
Fuzzy PID


Torque vs. time
Torque [N-m]
time [s]
PID
Fuzzy PID





8 Discussion

The results show that the Fuzzy-PID controller provides better rise and settling times than the PID controller. The mean square error for both controllers is similar, with the PID controller performing slightly better. However, the Fuzzy-PID controller exhibits a higher percentage overshoot, particularly when the initial slip ratio is $k = 0.15$. To reduce this, introducing a derivative gain is necessary.

For real-world use, the Fuzzy-PID controller must integrate the derivative gain within the fuzzy inference system. Additionally, extensive testing is required to adapt to changes in the optimal slip ratio. In the case of varying road conditions, the Fuzzy-PID controller can be coupled with the Recursive Least Squares (RLS) algorithm, as described in the paper *"Study on Optimal Slip Ratio Identification and Traction Control for Electric Vehicles"*, to determine the optimal slip ratio in real time.

References

1. Park, Jong Hyeon, and Kim, Chan Young. "Wheel Slip Control in Traction Control System for Vehicle Stability," 1999.

2. Jung, Hun Sang, Kwak, Byung Hak, and Park, Young Jin. "Development of Traction Control System," 2000.

3. Chao, LiBo, Chu, Liang, Ou, Yang, and Lu, WenBo. "Traction Control Algorithm Based on Fuzzy PID and PWM Modulation," 2011.

4. Gu, Qiang, and Cheng, Xiusheng. "Study on Optimal Slip Ratio Identification and Traction Control for Electric Vehicle," 2011.

5. Dahmani, H., Pages, O., and El Hajjaji, A. "Traction Control System Using a Fuzzy Representation of the Vehicle Model," 2015.

6. Salim, and Ohri, Jyoti. "FUZZY Based PID Controller for Speed Control of D.C. Motor Using LabVIEW," 2015.