Jurnal Personalia Pelajar 29(1): 401-408
https://doi.org/10.17576/personalia.2901.2026.41
ISSN 0128-2735

Enhancing the LRT Braking System Using Fuzzy Logic for Improved Safety and Passenger Comfort

(Menambah baik Sistem Brek LRT Menggunakan "Fuzzy Logic" untuk Keselamatan dan Keselesaan yang Lebih Baik Kepada Pengguna)

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ABSTRACTS

This paper presents a study on improving the braking system of Malaysia's Light Rail Transit (LRT) to adress the problem of abrupt stops and passenger discomfort. Current braking practices often lead to sudden deceleration, causing safety risks such as falls and collisions, in addition to a negative passenger experience. To overcome this challenge, we propose the integration of a fuzzy logic control (FLC) system into the existing LRT braking mechanism. Unlike conventional braking systems that apply fixed thresholds of deceleration, fuzzy logic enables adaptive and gradual braking by processing real-time data such as train speed, stopping distance, and track conditions. A prototype was developed using Arduino UNO, a toy train model, and ultrasonic sensors to simulate and evaluate the effectiveness of fuzzy logic control. Comparative experiments between conventional braking and fuzzy-controlled braking demonstrated significantly smoother deceleration, reducing jolts and passenger instability. The results suggest that fuzzy logic provides a feasible and cost-effective solution for enhancing both safety and comfort in Malaysia's LRT system without major infrastructure changes. The study further identifies limitations such as sensor reliability and coding constraints, while recommending future integration of neuro-fuzzy systems, multi-sensor input, and real-world simulation environments. Overall, this research provides a practical framework for advancing urban rail safety and passenger satisfaction in Malaysia.

Keywords: Fuzzy logic, braking system, LRT, safety, passenger comport.

ABSTRAK

Kertas ini membentangkan kajian untuk menambah baik sistem brek Transit Aliran Ringan (LRT) Malaysia bagi menangani masalah hentian secara mengejut dan mengurangkan ketidakselesaan penumpang. Sistem brek semasa sering melakukan hentian secara mengejut, menimbulkan risiko keselamatan seperti kejatuhan dan pelanggaran, selain memberikan pengalaman negatif kepada pengguna. Untuk mengatasi cabaran ini, kami mencadangkan integrasi sistem teknologi "Fuzzy Logic"(FLC) ke dalam mekanisme brek LRT sedia ada. Berbeza dengan sistem brek konvensional yang menerapkan ambang nyahpecutan yang tetap, fuzzy logic membolehkan pembrekan berlaku secara adaptif dan berperingkat dengan memproses data dalam masa nyata seperti kelajuan kereta api, jarak hentian, dan keadaan landasan. Satu prototaip telah dibangunkan menggunakan Arduino UNO, model kereta api mainan, dan sensor ultrasonik untuk mensimulasikan dan menilai keberkesanan "sistem kawalan fuzzy logic. Ekoran eksperimen perbandingan antara brek konvensional dan sistem brek kawalan fuzzy logic, fuzzy logic menunjukkan kemerosotan kelajuan yang jauh lebih lancar, pengurangan hentakan dari brek mengejut dan ketidakstabilan penumpang berbanding brek konvensional. Dengan ini, keputusan menunjukkan bahawa fuzzy logic merupakan satu pendekatan penyelesaian yang berkesan serta menjimatkan kos dalam usaha meningkatkan tahap keselamatan dan keselesaan dalam sistem LRT Malaysia tanpa memerlukan sebarang perubahan besar terhadap infrastruktur sedia ada. Kajian ini juga mengenal pasti halangan dan batasan sedia ada seperti kebolehpercayaan kepada sensor serta kekangan dalam pengekodan, sambil mengesyorkan integrasi sistem "neuro-fuzzy" , input berbilang sensor, dan simulasi dalam persekitaran dunia sebenar dalam penambahbaikan akan datang. Secara keseluruhannya, penyelidikan ini menyediakan kerangka praktikal untuk memajukan keselamatan rel bandar dan kepuasan penumpang di Malaysia.

Kata kunci: Fuzzy logic, sistem brek, LRT, keselamatan, keselesaan penumpang.

INTRODUCTION

Malaysia's Light Rail Transit (LRT) system is a vital part of the Klang Valley's public transportation network, serving thousands of commuters daily. As urbanization and population density increase, reliable and safe public transport has become not only convenient but also necessary for sustainable mobility. Despite the many benefits of the LRT system, one significant problem has been reported repeatedly by passengers: a sudden and abrupt stopping motion of trains.

When the braking system applies sudden deceleration, passengers often lose their balance, collide with one another, or experience discomfort from unexpected jolts. This situation is not only inconvenient but also dangerous, particularly for elderly passengers, children, and women. Unlike the Mass Rapid Transit (MRT) system, which provides women-only coaches to mitigate some of these risks, the LRT system lacks such designated spaces, increasing the likelihood of unconfortable or unsafe interactions when sudden stops occur.

Azlan et al. (2024) reported that passenger satisfaction with the LRT depends significantly on comfort and perceived safety. The current braking practice makes a negative impact on both aspects. Moreover, the Phypox mobile application analysis conducted during preliminary testing revealed a clear difference between LRT and MRT acceleration-time graphs. MRT braking curves showed gradual deceleration, whereas LRT graphs displayed sharp spikes in deceleration near station stops. These findings confirm both objectively and subjectively that LRT braking issue is real and urgent.

Globally, braking system innovations in urban rail transport have emphasized regenerative braking, advanced control algorithms, and predictive systems to optimize safety, energy efficiency, and ride comfort (Dalimi, 2023). Few studies, however, have explored the application of "fuzzy logic" - a soft computing technique inspired by human reasoning- for train braking control. Fuzzy logic enables control decisions in uncertain or imprecise conditions, such as varying passenger loads, track gradients, and unexpected stops. Its ability to use linguistic variables like "slow," "fast," "close," or "far" makes it uniquely suited for systems where rigid control laws couse abrupt outputs.

This paper aims to fill the gap by applying fuzzy logic control (FLC) to Malaysia's LRT braking system. We propose and test a fuzzy-controlled braking prototype using an Arduino-based model train, comparing it against conventional braking mothods. The study evaluates whether fuzzy logic can provide smoother stops, enhance safety, and improve overall passenger experience. The objectives of this study are as follows,

i. To improve passenger safety by minimizing falls, conditions, and discomfort caused by abrupt braking.
ii. To enhance comfort by reducing shocks and jolts during deceleration.
iii. To design and test a prototype braking system using fuzzy logic control.
iv. To identify the challenges, limitations, and opportunities of applying FLC in real LRT systems.
v. To recommend pathways for integrating fuzzy logic with Malaysia's existing rail infrastructure.

LITERATURE REVIEW

Existing LRT braking methods

Railway braking systems play a central role in ensuring both passenger safety and operational efficiency. In light rail systems such as Malaysia's LRT, braking must balance the competing needs of rapid deceleration for safety and gradual stopping for comfort. Traditionally, LRT braking systems have been based on a combination of electric braking (including dynamic and regenerative types) and mechanical braking (such as pneumatic or spring-applied brakes). This dual approach allows energy recovery during high-speed deceleration and ensures reliable stops at low speeds or emergencies.

Dynamic and regenerative brakes are operated by converting the train's kinetic energy into electrical energy, which can be dissipated as heat or returned to the power grid (Dalimi, 2023). Mechanical brakes, on the other hand, rely on friction and pressure to bring trains to a halt. They are activated when electric braking becomes ineffective at low speeds or when emergency conditions require immediate intervention.

However, the limitation of this system lies in the rigidity of control algorithms. Because traditional systems depend on predetermined threshold values for activation, they lack the ability to respond smoothly to variable conditions such as train load, track gradient, or humidity. Consequently, when the braking system suddenly transitions from electric to mechanical control, passengers experience abrupt jerks and discomfort the exact phenomenon observed in Malaysia's LRT system.

Passenger comfort and safety

Passenger comfort and safety are crucial factors that determine the public's willingness to use mass transit. As Azlan et al. (2024) emphasizes, perceptions of comfort and safety strongly influence ridership satisfaction and trust in public transportation services. Abrupt stops or jerky movements erode this confidence, leading passengers to prefer private vehicles even when public systems are more efficient or affordable.

Passenger safety in public transport involves not only the prevention of physical injuries but also the assurance of psychological and social comfort. In the context of Malaysia's LRT system, the absence of women-only coaches has amplified concerns about personal space and security, particularly during sudden braking events where unintentional physical contact is more likely to occur. Lee (2024) highlights that infrastructure and operational improvements that enhance comfort can directly contribute to ridership growth and support broader sustainability goals under Malaysia's National Transport Policy.

From an ergonomic perspective, sustained exposure to sudden deceleration can lead to muscular strain and balance-related injuries. In densely crowded carriages, even minor jerks can cause domino-like effects, heightening the risk of falls. Thus, braking comfort is not merely an issue of convenience but a public safety imperative.

Fuzzy logic in control systems

The concept of fuzzy logic was first introduced by Lotfi Zadeh in 1965 as a method for handling uncertainty and imprecision in human reasoning. Unlike binary logic systems that evaluate conditions as strictly "true" or "false," fuzzy logic allows for degrees of truth - values between 0 and 1 - corresponding to human linguistic reasoning such as "somewhat fast," "moderately near," or "slightly braking."

Fuzzy logic control (FLC) has been successfully applied in many engineering fields, including manufacturing process optimization (Basu & Narayan, 2011), energy management, robotics, and vehicle systems. Knapp (2007) explains that the key strength of fuzzy systems is their ability to approximate nonlinear processes without requiring a precise mathematical model. This makes them ideal for dynamic environments such as train braking, where conditions continuously change and perfect modeling is impractical.

In transportation systems, FLC has proven valuable in automotive braking systems (ABS), aircraft landing gear control, and energy-efficient electric train braking (Sadollah, 2018). In these applications, fuzzy logic enables adaptive decision-making based on multiple sensor inputs, adjusting braking pressure dynamically to achieve smoother motion and greater control stability.

Research gap

Despite advances in fuzzy control technology, its application to Malaysia's public rail systems remains minimal. Most existed studies focused on passenger satisfaction, maintenance, or energy optimization rather than control systems in Malaysia. There is a great lack of integration between technical innovation and user experience in the previous research - a gap this study aims to bridge.

By adopting fuzzy logic, the LRT system could achieve both mechanical reliability and enhanced human comfort without overhauling the existing braking infrastructure. Therefore, this research contributes not only to a prototype demonstration but also to a conceptual framework for how smart control can modernize Malaysia's aging LRT technology sustainably.

METHODOLOGY

This research adopts an experimental-prototyping approach that combines problem verification, design simulation, and comparative testing. Each stage aims to validate the effectiveness of fuzzy logic to improve braking comfort and safety.

Problem verification

Before implementing a solution, it was crucial to confirm that abrupt braking is a measurable problem rather than a subjective complaint. The research team employed the Phyphox mobile application, developed by RWTH Aachen University, to record acceleration data in both the LRT and MRT systems (Staacks et al., 2018).

A smartphone was placed parallel to the passenger seat, with axes aligned along the train's movement (x-axis), lateral direction (y-axis), and vertical direction (z-axis). The acceleration rate was monitored during normal stops at several stations. The temporal variation of acceleration rate is shown in Figure 1 for MRT and in Figure 2 for LRT. Figure 2 shows an abrupt fluctuation at the end of each trip in LRT, characterized by a sudden negative acceleration peak followed by a rebound - a “dip-spike” pattern. In contrast, the MRT shows a gradual curve with no abrupt deceleration in Figure 1.

These results confirme that LRT braking involves significantly higher instantaneous deceleration, validating anecdotal passenger feedback and justifying the need for a smoother control mechanism.

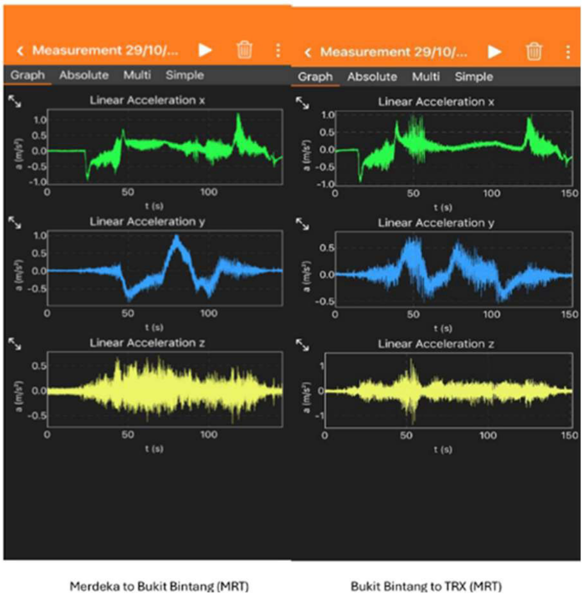

FIGURE 1: Temporal change of acceleration rate in MRT.

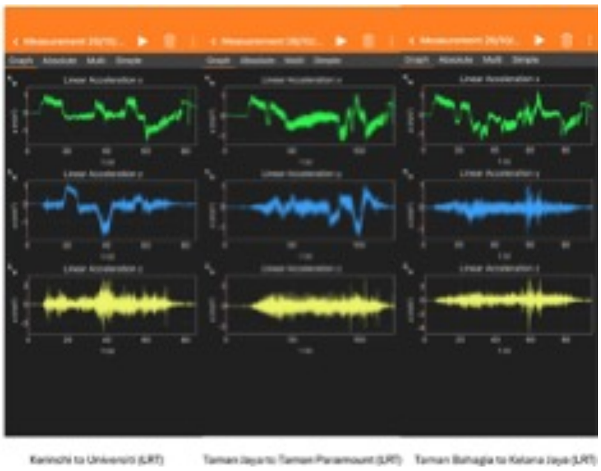

FIGURE 2: LRT Acceleration graph

Prototype design

To test fuzzy logic control under controlled conditions, a miniature simulation model was developed. The design incorporated:

i. Arduino UNO (microcontroller) - serves as the system’s core processor, executing fuzzy logic rules and adjusting motor speed accordingly.
ii. L298N Mortor Driver - provides current amplification and direction control for the train mortor.
iii. Ultrasonic sensor - measures distance between the train and the stopping point.
iv. Toy train model - represents the scaled-down vehicle.
v. 12V AC/DC adapter - supplies consistent electrical power.
vi. Jumper wires and breadboard connections - facilitate modular connections and easy adjustments.

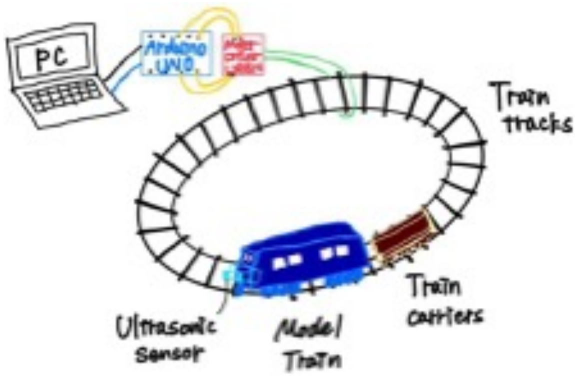

FIGURE 3: Schematic diagram showing a Model mock-up

The fuzzy logic system was configured using triangular membership functions for two main inputs: speed and distance. These functions assigned qualitative categories ("fast," "medium," "slow" for speed; "far," "near," "very near" for distance). The output variable - braking intensity- was defined linguistically as "soft," "moderate," or "strong."

The Arduino code translated these fuzzy rules into executable logic, using conditional ("if") and iterative ("while") loops to dynamically adjust the motor speed. For example, if the train was both "fast" and "near," the output braking command increased proportionally; if it was "slow" and "very near," the brake was applied softly, ensuring a gentle stop.

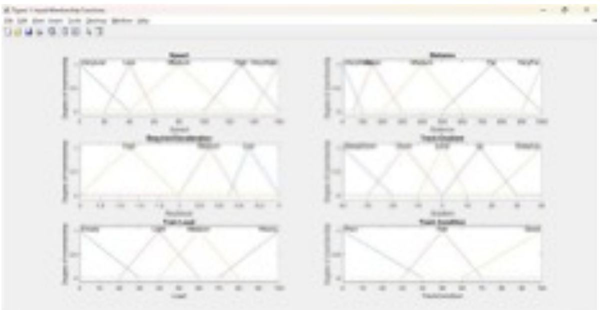

FIGURE 4: Input membership function plotted against multiple parameters

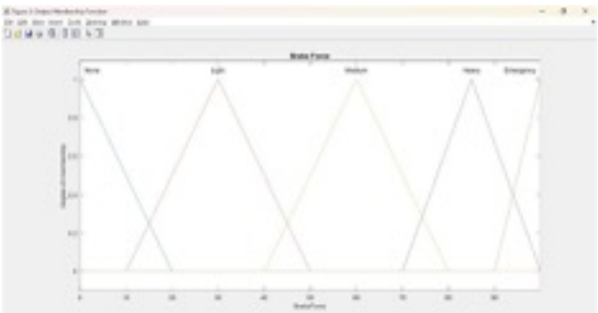

FIGURE 5: Output membership functions plotted against brake force

This way, we don't need to pick an exact speed letting the fuzzy logic itself to figure out how much the speed fits into these categories, in this case the membership function. After knowing this concept, then we can move into making the actual coding using Arduino UNO to demonstrate this fuzzy logic.

```
const int motorPin1 = 9, motorPin2 = 10, enablePin = 5;
float motorSpeed = 0.0;
const float maxSpeed = 255.0, minSpeed = 0.0;
const float decelerationStep = 0.5;
const int stopDelay = 50;
```

FIGURE 6: Arduino UNO Code (i)

In the initial phase of the coding, we implemented the fuzzy logic by setting the code with the term “decelarationStep” and “stopDelay”. This term will be the ranges of values for implementation of fuzzy logic because as shown earlier, this term relates with the triangle membership function with this “graduality” and the “delay” we put into this. This way, the train can follow the setting set up and stop gradually instead of stopping suddenly as current LRT braking system.

```
void gradualStop() {
  if (isRunning) {
    while (motorSpeed > minSpeed) {
      motorSpeed -= decelerationStep;
      if (motorSpeed < minSpeed) motorSpeed = minSpeed;
      analogWrite(enablePin, (int)motorSpeed);
      delay(stopDelay);
    }
    digitalWrite(motorPin1, LOW);
    digitalWrite(motorPin2, LOW);
    isRunning = false;
    Serial.println("Motor stopped.");
  }
```

FIGURE 7: Arduino UNO Code (ii)

Following the setting “set up” earlier, to further implement the fuzzy logic we have use the “if” and “while” dialogue to follow the fuzzy logic setting. The "if" statement in this is used to check certain conditions (like a sensor reading or user input) and then apply a fuzzy rule to make decisions. This is a basic example of using "if" to handle different inputs. The input is checked, and based on the command, we set the motor speed. This could be seen as applying a fuzzy rule:

- "Slow" means a low speed (e.g., motor speed = 50).
- "Moderate" means a medium speed (motor speed = 127).
- "Fast" means a high speed (motor speed = 255).

But to make the decision more complex and precise, we implemented *gradual speed adjustment*, allowing the motor speed to change in small increments rather than jumping directly from one value to another. For the term “while” it is used to continuously check and apply fuzzy logic rules, for example, adjusting motor speed until a certain condition is met. Using "while", we can gradually loop the speed to decrease the motor speed as long as the sensor input is above a certain threshold. The motor continues to slow down in small steps (Figure 6) until the condition is no longer true.

By using only these simple terms ("if" and "while"), we can implement fuzzy logic in a way that makes our system more flexible, able to handle "almost true" or "somewhat false" conditions rather than just strict binary decisions, which is essential for controlling systems especially for train braking systems.

Experiments

Two models were tested under identical conditions:

- Model A (conventional braking) - direct stop without fuzzy logic.
- Model B (fuzzy-controlled braking) - adaptive deceleration using fuzzy logic.

Both models were run with identical load masses, track lengths, and initial speeds. The evaluation focused on deceleration smoothness and load stability. Observations were recorded visually and through motion data captured using video analysis.

RESULTS AND DISCUSSION

Prototype outcomes

The comparative experiment demonstrated clear differences between the two braking models. In Model A, the abrupt stop caused the attached load compartments to lurch forward and collide with the lead car, replicating the jerky motion observed in real LRT operations. In contrast, Model B using fuzzy control achieved a smooth, gradual stop. The connected loads remained stable, showing no noticeable oscillation.

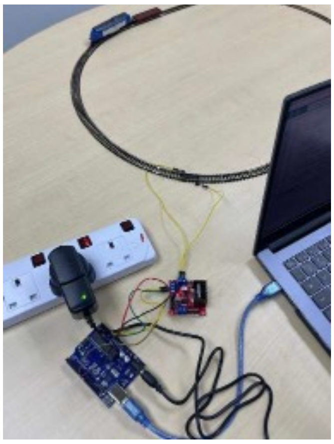

FIGURE 8: Photograph showing the actual model

These results align with prior studies that have reported smoother transitions and reduced system stress in fuzzy-controlled braking systems (Basu & Narayan, 2011). The adaptive control algorithm continuously adjusted the braking force rather than applying discrete “on–off” commands, effectively minimizing inertial shocks.

Implications for passenger safety

Translating these findings to a full-scale system, fuzzy braking would reduce passenger injury risks during sudden deceleration. Passengers would be less likely to lose balance, even when standing or holding onto handrails. The risk of unintentional physical contact in crowded cars - a social and safety concern especially for female passengers - would also decrease. Thus, fuzzy logic contributes not only to physical safety but also to social comfort in a shared public environment.

Comfort and psychological perception

Comfort in public transport is not limited tophysical stability; it also involves perceived smoothness, quietness, and predictability. A braking profile that decelerates gradually contributes to a sense of control and reliability. Lee (2024) noted that improved comfort significantly increases passengers’ confidence in using urban rail systems. With fuzzy control, the LRT could achieve passenger satisfaction levels comparable to the newer MRT system, encouraging modal shift from private vehicles.

Challenges and limitations

- Despite the success of the prototype, several challenges emerged:
- Sensor durability: The ultrasonic sensor failed after extended use, highlighting the need for more robust hardware in real-world applications.
- Electrical instability: Recurrent jumper wire failures suggested voltage inconsistencies in the Arduino setup.
- Coding complexity: Implementing fuzzy logic required precise programming and tuning, which proved time-consuming given the team’s limited coding experience.
- Resource limitations: The prototype used only two input variables due to hardware constraints; in practice, more parameters (track gradient, passenger load, humidity) would be necessary.

Discussion and interpretation

The results suggest that fuzzy logic control provides a scalable solution to Malaysia’s LRT braking issues. The technology can be integrated into existing systems with minimal infrastructure modification - primarily through software upgrades and sensor installation. However, real-world deployment would require rigorous testing under different operational conditions, including emergency stops, wet tracks, and full-capacity passenger loads.

Future versions could incorporate neuro-fuzzy systems, which combine fuzzy logic with artificial neural networks for self-learning capabilities. Such systems can automatically adjust membership functions and control parameters based on continuous data collection, improving precision and robustness.

Moreover, connecting the fuzzy braking system with a centralized train control network could enable real-time coordination between multiple trains, optimizing both safety and energy efficiency across the entire LRT line.

CONCLUSION

This study dmeonstrates that Malaysia's LRT braking system, while functional, needs to produce significant safety and comfort challenges against the issues caused by abrupt stops. By applying fuzzy logic control through an Arduino-based protptype, we show that braking can be made smoother, more adaptive, and safer for passengers.

The results confirm that fuzzy logic offers a cost-effective upgrade pathway without requiring full-scale infrastructure replacement. Limitations remain, particularly in sensor durabilitiy and coding, but the potential for real-world application is clear. Future research should integrate advanced neuro-fuzzy systems, multi-sensor data fusion, and large-scale simulations to validate effectiveness under diverse prerating conditions.

Consequestly, improving the braking system is not just a technical upgrade it is a social necessity to ensure that Malaysia's public transportation remains safe, reliable, and attractive for its growing urban population.

APPRECIATION

The author would like to show her sincere appreciation to Prof. Dr. Hiromi Motiyama who supervised us in the class, which the author developed this system. Also, the author thanks to Mr. Asyraf Kazuki Bin Abdul Zaki and Mr. Ong Khai Sern who are team members of this project. This study was supported financially by JACTIM (The Japanese Chamber of Trade & Industry, Malaysia) Foundation.

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