

Z-number-based traffic signal control

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Traffic congestion is a significant issue in many large cities globally. This congestion can negatively impact a country's economy, increase costs, hinder development, and contribute to environmental pollution. This study focuses on creating a Z-number-based traffic signal system with a dynamic cycle length. The development of this type of traffic signal system relies on Z-numbers, which are designed to handle uncertainty and vagueness in input and output parameters. Z-numbers are effective in managing the imprecision often found in traffic systems. The key input parameters for this system are traffic density and traffic flow. The Z-number-based traffic signal controller processes these inputs using a fuzzy inference system to calculate the optimal cycle length. The simulation of this system is performed using Z-lab software. Based on the traffic conditions, the signal cycle length is adjusted, reducing vehicle waiting times at intersections.

Z-number; traffic signal; Z-lab software; Traffic congestion; Z-inference; Z-IF-THEN rules.

INTRODUCTION

The traffic signal control problem is a basic aspect of modern urban infrastructure, impacting everything from safety and efficiency to environmental sustainability and economic productivity. Properly optimized traffic signal management systems are essential for creating smarter, safer, and more efficient cities that can handle growing populations and increasingly complex transportation needs.

The Traffic Signal Control Problem (TSCP) is of critical importance in real life for several reasons. Efficient traffic signal management directly impacts daily life, urban development, and public safety. The main goals are to reduce congestion, reduce waiting times, and ensure safety for all road users.

Poorly managed traffic signals contribute to congestion, causing long wait times at intersections and delays in vehicle movement. Efficient traffic signal control helps minimize these delays, improving overall traffic flow and reducing bottlenecks.

This research focuses on developing a Z-number based traffic signal system with a dynamic cycle length to address traffic congestion in large cities. Traffic congestion can harm the economy, increase costs, hinder development, and worsen environmental pollution. The system uses Z-number theory to manage uncertainty and vagueness in traffic data, specifically traffic density and flow. These inputs are processed through a Z-number based inference system to calculate the signal cycle length. By adjusting the cycle length based on real-time traffic conditions, the system aims to reduce vehicle waiting times at intersections.

There are various traffic signal control systems. The information used in these systems cannot always be expressed precisely. Various types of uncertainties are widely used to characterize the input and output parameters of the system – including fuzzy, stochastic (probabilistic) and imperfect uncertainties. In modern scientific research, the description of information arising from dynamic

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factors such as experimental errors, environmental factors (temperature and climate changes), instability of technical equipment and traffic flow is of particular relevance.

Identification of the ontological nature of the existing uncertainty is of crucial importance in the process of selecting an information processing methodology. In this regard, fuzzy logic and its hybrid combinations are considered a priority direction in modern scientific paradigms in modeling complex systems.

One of the fundamental components of fuzzy logic, as proposed by Professor Zadeh, is probabilistic reasoning. In modern scientific paradigms, the probabilistic approach constitutes a fundamental methodological basis for the representation of uncertain knowledge structures, as well as the mathematical modeling and analysis of random phenomena. Furthermore, probabilistic reasoning does not make a distinction between knowledge uncertainty and errors that contribute to uncertainty and incomplete knowledge.

Probabilistic reasoning (PR) involves incomplete knowledge, computational complexity, and the axiomatic limitations of classical probability theory, but it does not offer a comprehensive methodological framework for a deep understanding of these fundamental problems. The integration of probabilistic reasoning and fuzzy set theory forms the conceptual foundation of soft computing. Thus, it is clear that fuzzy logic theory is a highly effective tool for representing uncertain knowledge or knowledge given in linguistic form.

However, combining data expressed by both fuzzy logic and probabilistic reasoning presents a complex challenge, and there is limited research in this area. This article explores the application of Z-reasoning in the example for a traffic signal controller.

In scientific literature there are some common methods used to solve traffic signal control problems. They are characterized by a set of disadvantages.

In the research paper [Thu19], the issue of optimizing the coordination of fixed-time traffic signals for practical applications was studied. The study integrated two fundamental models: an analytical optimization model based on a periodically time-expanded network approach and a co-evolutionary transport simulation that provides verification of the obtained schedules in large-scale, real-world traffic scenarios.

The integration methodology of both models, the processes of parameter adaptation and iterative improvement of the results were analyzed in detail. The optimized fixed-time signal plans were evaluated in comparison with other existing control methods. The results of the study prove that optimized fixed-time signals also significantly improve the performance of adaptive (actuated) control systems (actuated signal control).

In Fixed-Time Control method the signal timings are predetermined and do not change, regardless of how busy the traffic is. While simple, this approach can be inefficient during times of fluctuating traffic.

The authors of the paper [Lur11] discussed how to determine the optimal green split allocation at a signalized intersection controlled by semi-actuated signals within an urban traffic network. Discussed problem is formulated as a Mathematical Program with Equilibrium Constraints.

It is known that actuated control methods use sensors to detect vehicles at intersections and adjust signal timings based on the real-time presence of vehicles, offering greater flexibility compared to fixed-time systems. The inaccuracy of the data used in solving the problem considered in this article was not taken into account.

Adaptive Traffic Signal Control (ATSC) is an effective method for enhancing the efficiency of signalized intersections. Several ATSC algorithms minimize delays, reduce queue lengths, or maximize vehicle throughput. However, most existing ATSC algorithms primarily focus on improving traffic flow and do not account for optimizing traffic safety.

In [Ess20], a self-learning ATSC algorithm is proposed that aims to improve the safety of signalized intersections. This algorithm is based on the Reinforcement Learning (RL) approach, which al-

lows the system to learn and adapt over time based on traffic conditions. Through this dynamic adjustment, the system not only optimizes signal timing and reduces delays but also enhances safety by considering factors related to accident prevention and safe traffic flow.

The Fuzzy Logic Control (FLC) approach [Lee90] for traffic signal management is widely recognized in scientific literature as an effective method for optimizing signal timings in conditions of uncertainty or imprecision. Unlike traditional traffic control systems that depend on fixed, precise sensor inputs, FLC can manage fluctuating and unpredictable traffic conditions, such as varying traffic flow, vehicle density, and waiting times.

In FLC, parameters like traffic density, vehicle flow, and waiting time are represented as fuzzy sets (e.g., “low,” “medium,” or “high”) instead of precise numerical values. The system then uses a series of expert-based “if-then” rules to determine the appropriate signal timings. For example, a rule might state, “If traffic density is high and waiting time is long, then increase green time.” These rules are processed through a fuzzy inference system to generate optimal signal timing, adjusting the lights in real-time based on traffic conditions.

FLC can effectively process imprecise or incomplete data, which makes it suitable for dynamic traffic conditions. FLC can adapt to a wide range of traffic scenarios. FLC helps reduce vehicle waiting times and overall congestion.

Fuzzy logic control is particularly useful for complex traffic networks where traditional methods, especially those with nonlinear relationships and short-term uncertainty, are lacking. This approach is effective tool in conditions of information inaccuracy, but the degree of confidence in the uncertainty is not taken into account. In this case, a Z-number based approach [Ali21, Gar20, Gar22] is needed.

In this study, the traffic signal control problem is considered using Z-valued approximate reasoning. Z-number-based control is a traffic signal management approach that combines fuzzy logic and probabilistic reasoning to effectively handle uncertainty in traffic data. Z-numbers are a mathematical tool designed to represent and process vague or uncertain information by integrating both fuzzy sets and probability, allowing for more flexible and accurate decision-making.

In Z-number based traffic signal control, the system adjusts the signal cycle length dynamically according to real-time traffic conditions such as traffic flow, density, and waiting times. The use of Z-numbers allows the system to account for uncertainty and imprecision in these traffic parameters, providing a more adaptable and robust control mechanism.

The presented article consists of four main structural sections. The second section explains the theoretical foundations of the research and fundamental information on the topic. The third section is devoted to the conceptual formulation of the problem and the justification of the proposed methodological solutions. Finally, the fourth section summarizes the results of the research and presents relevant conclusions about future prospects.

PRELIMINARIES

Definition 1. Mathematical representation of a trapezoidal fuzzy number [Ban11] as follows:

$$f(x, a, b, c, d) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right), \quad (1)$$

where a, b, c, d are the parameters that define the shape of the trapezoid, x is the variable for which the membership function is being evaluated.

Definition 2. A discrete Z-number [Zad10, Ali15]. is an ordered pair $Z = (A, B)$ where A is a discrete fuzzy number playing a role of a fuzzy constraint on values that a random variable X may take: X is A , and B is a discrete fuzzy number with a membership function $\mu_B: \{b_1, \dots, b_m\} \subset [0, 1]$ playing a role of a fuzzy constraint on a value of probability measure

$$P(A) = \sum_{x \in X} \mu_A(x)p(x) \quad (2)$$

of A : $P(A)$ is B .

Definition 3. Z IF-THEN rules [Ali17].

If X_1 is $Z_{X_1,n} = (A_{X_1,n}, B_{X_1,n})$ and, ..., and X_m is $Z_{X_m,n} = (A_{X_m,n}, B_{X_m,n})$, then Y is $Z_Y = (A_{Y,n}, B_{Y,n})$ where $Z_{X_m,n} = (A_{X_m,n}, B_{X_m,n})$ is the Z-sets based inputs and $Z_Y = (A_{Y,n}, B_{Y,n})$ is Z sets-based outputs of the rules.

Definition 4. Z-reasoning algorithm [Ali16]. Solution method of the problem described Z-rules consists of the following steps:

1. Calculation of fuzzy relation matrices on the rules. $R_s, s = 1...6, R_s \subseteq \tilde{E}_i \times \tilde{U}_j$.

2. Formulation of the union of fuzzy relation matrices (R): $R = \cup R_s, s = 1, \dots, 6$. After defining individual fuzzy relation matrices for each rule, these matrices are combined into a single fuzzy relation matrix R . This union represents the overall relationship between all inputs and outputs across the rules.

3. Calculation of the membership function using the compositional rule of inference (CRI). CRI is applied to calculate the membership function. This rule allows the fuzzy system to infer the output membership based on the union of fuzzy relations from step 2. The compositional rule of inference works by combining the fuzzy relation matrices to derive a fuzzy output that corresponds to the given inputs:

$$\mu_Y(u) = \max_y \min[\mu_X(x), \mu_R(y, x)]. \quad (3)$$

4. Calculation of B part of Z-number. This step involves defining a set of probability distributions (G) by selecting specific support points (B) over the inputs of the rules. Support points are specific values used in the fuzzy logic system to represent the input.

5. Aggregation of distributions. The probability distributions obtained from step 4 are combined (aggregated) using a weighted sum probability method. This step helps to combine different probabilities in a meaningful way based on their importance (weights).

6. Defining distributions over outputs. A set of probability distributions (G) is defined again, but this time over the outputs of the rules. Similar to step 4, this involves selecting support points over the outputs of the fuzzy rules.

7. Calculating minimum values for each rule. For each rule, the minimum values are calculated using the distributions of both the inputs and the outputs. This step helps determine the most relevant or smallest value for each rule to make accurate decisions.

8. Obtaining the set of probability distributions. After calculating the minimum values for each rule, the next step is to aggregate the results again, using the same probability aggregation method as in step 5.

9. Calculating probability distributions over new input.

10. Calculating the distance between two vectors using Hellinger distance (4) [Ife12]:

$$ZHD(P_{z_1}, P_{z_2}) = \min_{p_{z_i} \in G} \left(\frac{1}{\sqrt{2}} \left(\sum_{j=1}^k (p_{z_1j}^{1/2} - p_{z_2j}^{1/2}) \right)^{1/2} \right). \quad (4)$$

11. Calculation of similarity measure (5) [Ali17b]:

$$SM = 1/(1 + ZHD). \quad (5)$$

A similarity measure is calculated to determine how close or similar the distributions or inputs are.

12. Calculating output support points and membership value. Using the A part of the Z-set, the probability distributions, and the similarity measure, calculate the support points for output B .

NUMERICAL EXAMPLE AND SOLUTION OF THE PROBLEM

Numerical example. Z-number based traffic signal control system is represented by production rules consisting of two inputs and one output. Here traffic density and traffic flow are inputs,

and cycle length is output. The goal is to define the cycle length depending on traffic density and traffic flow.

There are five descriptive values for each of input parameters and for output parameter of the control traffic signal: Very Small (VS), Small (S), Medium (M), Large (L), and Very Large (VL). Descriptive values of the *B* parts of the Z-number as follows:

$$\begin{aligned} \text{small sure (SS)} &= 0.31/0.72 + 1/0.73 + 0.37/0.74; \\ \text{medium (M)} &= 0.25/0.55 + 1/0.6 + 0.4/0.81; \\ \text{sure (S)} &= 0.11/0.71 + 1/0.81 + 0.31/0.91; \\ \text{very sure (VS)} &= 0.21/0.82 + 1/0.92 + 0.23/1. \end{aligned}$$

Z-number based values of inputs and output are described in Table 1. Z-number-based traffic signal control system is represented by production rules as follows:

- IF TD = (VS, VS) AND TF = (M, VS) THEN CL = (S, VS);
- IF TD = (VS, SS) AND TF = (L, S) THEN CL = (M, SS);
- IF TD = (VS, S) AND TF = (VL, VS) THEN CL = (L, VS);
- IF TD = (S, SS) AND TF = (VS, SS) THEN CL = (VS, SS);
- IF TD = (S, S) AND TF = (S, VS) THEN CL = (S, VS);
- IF TD = (S, VS) AND TF = (M, SS) THEN CL = (S, SS).

Table 1

Representation of inputs and output on the rules with Z-number

No	Traffic density (TD) $Z_{TD}(A, B)$	Traffic flow(TF) $Z_{TF}(A, B)$	Cycle length(CL) $Z_{CL}(A, B)$
1	(VS, VS) = [[0, 10, 10, 15], [0.82, 0.92, 0.92, 1]]	(M, VS) = [[500, 800, 800, 1100], [0.82, 0.92, 0.92, 1]]	(S, VS) = [[16.7, 25, 25, 35], [0.82, 0.92, 0.92, 1]]
2	(VS, SS) = [[0, 10, 10, 15], [0.72, 0.73, 0.73, 0.74]]	(L, S) = [[800, 1100, 1100, 1300], [0.71, 0.81, 0.81, 0.91]]	(M, SS) = [[25, 33.2, 33.2, 41.7], [0.72, 0.73, 0.73, 0.74]]
3	(VS, S) = [[0, 10, 10, 15], [0.71, 0.81, 0.81, 0.91]]	(VL, VS) = [[1100, 1500, 1500, 3000], [0.82, 0.92, 0.92, 1]]	(L, VS) = [[40, 50, 50, 61.8], [0.82, 0.92, 0.92, 1]]
4	(S, SS) = [[10, 25, 25, 40], [0.72, 0.73, 0.73, 0.74]]	(VS, SS) = [[0, 200, 200, 300], [0.72, 0.73, 0.73, 0.74]]	(VS, SS) = [[10, 16.7, 16.7, 21], [0.72, 0.73, 0.73, 0.74]]
5	(S, S) = [[10, 25, 25, 40], [0.71, 0.81, 0.81, 0.91]]	(S, VS) = [[200, 500, 500, 800], [0.82, 0.92, 0.92, 1]]	(S, VS) = [[16.7, 25, 25, 35], [0.82, 0.92, 0.92, 1]]
6	(S, VS) = [[10, 25, 25, 40], [0.82, 0.92, 0.92, 1]]	(M, SS) = [[500, 800, 800, 1100], [0.72, 0.73, 0.73, 0.74]]	(S, SS) = [[16.7, 25, 25, 35], [0.72, 0.73, 0.73, 0.74]]

In order to verify the methodology under consideration, simulation tests were performed using the Z-Lab software [Adi23]. This software environment allows for complex calculations based on fuzzy logic and, in particular, the theory of Z-numbers. Within the framework of the tests, various tests were performed taking into account descriptive variables and their corresponding reliability levels.

Test 1. The mathematical-logical formulation of the test is as follows:

Input 1 (Traffic density): “Low”, Reliability: “Sure”.

Input 2 (Traffic flow): “Very low”, Reliability: “Sure”.

Objective: To determine the optimal Cycle Length based on the given fuzzy inputs.

The Z-number structure used in this test simultaneously processes both the fuzziness of information (e.g., “low density”) and the subjective belief in the accuracy of that information (e.g., “degree of certainty”).

Answer: If traffic density is (Low, Sure) and traffic flow is (Very Low, Sure), then define cycle length is (Low, Small Sure).

Test 2. If traffic density is (Medium, Very Sure) and traffic flow is (Low, Sure) then define cycle length=?

Answer: If traffic density is (Medium, Very Sure) and traffic flow is (Low, Sure), then define cycle length is (Medium, Sure)

Z-lab software is a simulation tool designed to work with *Z-numbers* for modeling and solving complex systems [Adi23] where uncertainty, imprecision, and vagueness exist, particularly in fields like traffic management. Z-lab is commonly used for developing, testing, and evaluating systems that require handling fuzzy and probabilistic data. In this work we applied *Z-lab software* for solving traffic signal control problems.

CONCLUSION

This paper introduces a traffic signal controller based on Z-numbers. Obtained results show that Z-controller is more efficient than the fixed time traffic signal controller. The cycle time calculated through the Z-controller is more efficient than the fixed time traffic signal controller. The performance of Z-controller is highly dependent on the Z-rule base, so it is important to tune the Z-rules correctly. After performing the experiments on different input data sets, we get better performance of Z-number based traffic signal controller than the fixed time traffic signal control.

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МЕТАДАННЫЕ | METADATA

Заглавие: Управление светофорами на основе Z-чисел.

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Аннотация: Пробки на дорогах являются серьёзной проблемой во многих крупных городах мира. Эти пробки могут негативно влиять на экономику страны, увеличивать издержки, препятствовать развитию и способствовать загрязнению окружающей среды. Данное исследование посвящено созданию системы светофоров на основе Z-чисел с динамической длительностью цикла. Разработка такой системы светофоров основана на Z-числе, которые предназначены для обработки неопределённости и нечёткости входных и выходных параметров. Z-числа эффективны в управлении неточностью, часто встречающейся в системах управления дорожным движением. Ключевыми входными параметрами для этой системы являются плотность и интенсивность движения. Контроллер светофора на основе Z-чисел обрабатывает эти входные данные с помощью системы нечёткого вывода для расчёта оптимальной длительности цикла. Моделирование этой системы выполняется с использованием программного обеспечения Z-lab. В зависимости от дорожных условий длительность цикла сигнала корректируется, сокращая время ожидания транспортных средств на перекрёстках.

Ключевые слова: Z-число; светофор; программное обеспечение Z-lab; транспортная загруженность; Z-вывод; правила Z-ЕСЛИ-ТО.

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Key words: Z-number; traffic signal; Z-lab software; Traffic congestion; Z-inference; Z-IF-THEN rules.

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