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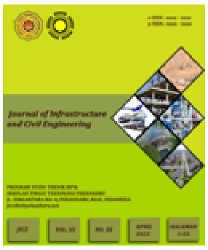

Application of Type-2 Fuzzy Logic to Signal Timing Control at Signalized Intersections: Addressing Traffic Data Uncertainty

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Abstract

Urban intersections are increasingly congested as motorized vehicle volumes continue to rise, while fixed-time signal control often fails to respond to dynamic traffic conditions. This review examines the use of Type-2 Fuzzy Logic (FL-T2) for adaptive signal timing control under traffic uncertainty and its relevance to Indonesian urban intersections. A systematic literature review was conducted on recent studies published between 2021 and 2025. The reviewed studies show that FL-T2 is generally built on fuzzification, rule-base formulation, inference, and defuzzification, with uncertainty represented through the Footprint of Uncertainty. The synthesis indicates that FL-T2 performs better than fixed-time control and Type-1 fuzzy logic in reducing delay, queue length, and saturation level, especially under fluctuating traffic conditions. Hybrid FL-T2 models with optimization algorithms also show stronger performance in simulation studies. However, practical implementation in Indonesia still depends on detector availability, data quality, computational feasibility, and institutional readiness. FL-T2 is therefore a promising adaptive control framework, but further local simulation and pilot testing are needed before field deployment.

Keywords: *Interval Type-2 Fuzzy Logic; adaptive signal control; traffic signal optimization; intersection performance; traffic uncertainty; systematic review*

1. Introduction

The massive growth in the volume of motorized vehicles in urban areas has positioned signalized intersections as critical points for the emergence of traffic congestion. This condition is further aggravated by the implementation of static or fixed-time signal control systems, which are designed based on historical data and are unable to respond dynamically to fluctuations in traffic flow. As a result, intersection efficiency declines significantly, vehicle delays increase, and long queues become a common occurrence during peak hours. [8] emphasized that rule-based control methods possess fundamental limitations in dealing with unpredictable changes in traffic flow, thereby necessitating an adaptive control approach capable of adjusting signal phase durations in real time based on actual field conditions.

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In an effort to overcome these limitations, fuzzy logic-based control has emerged as a popular solution due to its ability to emulate human reasoning and translate expert knowledge into numerical decisions without requiring a precise mathematical model. [7] demonstrated that an adaptive signal control system based on fuzzy logic, integrated with real-time vehicle detection from video surveillance cameras, was capable of producing more responsive phase control than conventional systems. Nevertheless, Type-1 Fuzzy Logic still exhibits a significant limitation, namely its inability to handle inter-personal uncertainty, as the membership function values are still defined as single deterministic numbers.

To address the limitations of Type-1 fuzzy logic, Type-2 Fuzzy Logic was developed with a three-dimensional membership function, enabling it to represent a higher degree of uncertainty. [9] demonstrated that the application of the Interval Type-2 Fuzzy Logic System (IT2FLS) in intersection control outperformed conventional methods in terms of queue length and the number of vehicle stops, as this system inherently accommodates input data uncertainty arising from traffic flow variability. This capability is highly relevant given that real-world traffic data inherently contain noise, random fluctuations, and inconsistencies that cannot be optimally handled by conventional fuzzy systems.

Furthermore, recent studies have demonstrated that hybrid algorithm-based optimization in Type-2 fuzzy controllers delivers significantly superior performance. [11] developed a hybrid control system that combines the Flower Pollination Algorithm with Type-2 Fuzzy Logic optimized using the Crow Search Algorithm, and achieved an approximately 32% improvement in performance compared with a fixed-time controller, while also surpassing the performance of a Type-1 fuzzy controller under various intersection geometry conditions. These findings reinforce the argument that Type-2 Fuzzy Logic is a highly competitive candidate for application in signal timing control at signalized intersections.

Based on the foregoing background, this study focuses on three main research problems. First, how can a signal timing control system at signalized intersections be designed using a Type-2 Fuzzy Logic approach that is capable of dynamically adapting to fluctuations in traffic volume? Second, how effective is Type-2 Fuzzy Logic in handling traffic data uncertainty compared with Type-1 fuzzy methods and fixed-time control? Third, what is the effect of implementing Type-2 Fuzzy Logic on the performance of signalized intersections as measured by average delay, queue length, and degree of saturation?

This study examines design and implement a Type-2 Fuzzy Logic-based signal timing control system for signalized intersections that is capable of effectively handling traffic data uncertainty, and to compare its performance with conventional control methods through measurable simulations. [1] noted that a well-designed fuzzy logic-based system can significantly reduce the average vehicle waiting time compared with other approaches, suggesting that further development using Type-2 fuzzy logic is expected to produce more substantial improvements. In addition, this study also aims to identify the optimal membership function and rule base parameters for urban traffic conditions in Indonesia.

The expected contributions of this study encompass two aspects. Theoretically, this study provides a scientific contribution in the form of a structured Type-2 Fuzzy Logic system design framework that may serve as a reference for future research in the field of intelligent traffic control. Practically, this study offers an alternative technological solution for traffic signal control that is more adaptive and efficient, with the potential to be implemented at signalized intersections in urban Indonesia in order to reduce vehicle delay, shorten queue length, and improve the overall level of service of intersections. [5] emphasized that intelligent and adaptive traffic signal control systems constitute an urgent necessity in urban areas experiencing continuous growth in traffic intensity, indicating that the practical significance of this study is highly relevant to contemporary urban transportation problems.

2. Methodology

This study employed a systematic literature review approach to examine the application of Type-2 Fuzzy Logic (FL-T2) in signal timing control at signalized intersections. The review focused on recent studies published between 2021 and 2025 in reputable journal articles, conference proceedings, and technical publications relevant to adaptive traffic signal control. The use of a systematic approach was intended to ensure transparency, consistency, and reproducibility in the identification and analysis of relevant studies.

Literature selection was conducted through a structured screening process based on predefined inclusion and exclusion criteria. The inclusion criteria comprised studies that explicitly discussed FL-T2, adaptive signal timing control, traffic uncertainty handling, intersection performance evaluation, or related intelligent transportation applications. Studies were excluded if they were unrelated to signalized intersection control, did not employ fuzzy logic-based methods, fell outside the publication period of 2021–2025, or lacked sufficient methodological and analytical information for review purposes. The selected literature was screened in stages to ensure that only studies with strong topical relevance and adequate scholarly quality were included in the final analysis.

The quality of the selected studies was assessed using criteria related to topic relevance, methodological clarity, theoretical contribution, and completeness of reported findings. Articles were retained only if they demonstrated clear research objectives, explicit methodological procedures, and interpretable results that could contribute meaningfully to the synthesis of FL-T2-based traffic control approaches. This quality assessment step was used to improve the credibility of the review and reduce the influence of weak or incomplete publications.

Data extraction was carried out using a structured review framework. The extracted information included the author and year of publication, research objectives, FL-T2 system architecture, fuzzification mechanism, rule-base formulation, inference procedure, type-reduction method, defuzzification technique, and reported performance indicators such as average delay, queue length, number of stops, and degree of saturation. Additional notes regarding the strengths, limitations, and implementation context of each study were also recorded to support deeper analysis.

The extracted data were synthesized through descriptive-comparative analysis. This synthesis method was used to identify recurring design patterns, compare different FL-T2 configurations, and evaluate the relative effectiveness of Type-2 Fuzzy Logic in handling traffic uncertainty under varying intersection conditions. The analysis also highlighted key implementation issues, including parameter selection, model complexity, and applicability to urban traffic characteristics. The review did not generate primary field data; instead, it produced a conceptual and analytical synthesis intended to provide a scientifically grounded basis for future simulation, validation, and implementation studies in the Indonesian urban traffic context.

Table 1. Research Methodology Framework

Research stage	Description of activity	Main focus	Expected output
Literature identification	Collecting journal articles, conference papers, and technical publications related to FL-T2 and signalized intersection control	Type-2 Fuzzy Logic, adaptive traffic signal control, uncertainty in traffic data	Initial pool of relevant references
Literature selection	Screening documents based on topical relevance, publication quality, and accessibility	Suitability to research objectives and analytical needs	Core references for detailed review
Conceptual data extraction	Extracting information on system components and control mechanisms	Fuzzification, FOU, rule base, inference, type-reduction, defuzzification	Analytical matrix of FL-T2 design elements
Comparative synthesis	Comparing findings across studies to determine the most effective control strategy	Delay, queue length, degree of saturation, flexibility, computational efficiency	Synthesized evidence base
Framework formulation	Developing a conceptual FL-T2 control design for urban intersections	Alignment between uncertain traffic inputs and adaptive signal timing outputs	Proposed research framework

Source: Data Research 2026

3. Results and Discussion

3.1. Design of the Type-2 Fuzzy Logic System

The reviewed studies show that a Type-2 Fuzzy Logic (FL-T2) signal timing controller is generally organized around four core components: fuzzification, rule-base construction, inference, and defuzzification. Its main advantage over Type-1 fuzzy logic lies in the use of the Footprint of Uncertainty (FOU), which allows the controller to represent imprecision in traffic inputs such as vehicle volume, queue length, and arrival rate more realistically. This is particularly important in urban intersections where traffic streams fluctuate rapidly and detector readings are often noisy, incomplete, or inconsistent.

However, the superiority of FL-T2 should not be interpreted as automatic or universal. Its performance depends strongly on the quality of the membership function design, the stability of the rule base, and the availability of input data that adequately reflect local traffic behavior. In the reviewed literature, FL-T2 tends to work best in environments with high variability, demand imbalance, and uncertain arrival patterns, because these conditions create exactly the type of ambiguity that FOU is designed to capture.

Several studies also indicate that FL-T2 becomes more effective when combined with optimization algorithms such as Crow Search Algorithm or learning-based methods. This suggests that FL-T2 is not merely a control rule system, but a flexible architecture whose effectiveness improves when parameter tuning is supported by optimization. At the same time, this added flexibility comes with a cost: more complex calibration, greater computational burden, and a stronger dependence on implementation expertise.

3.2. Comparative Effectiveness of FL-T2

The reviewed studies indicate that FL-T2 generally outperforms fixed-time control and Type-1 fuzzy logic in managing traffic uncertainty, but this advantage should be interpreted in a contextual rather than absolute manner. The main reason for this superior performance is that FL-T2 represents uncertainty explicitly through the Footprint of Uncertainty (FOU), allowing the controller to process ambiguous and fluctuating traffic inputs more robustly than Type-1 systems, which rely on single deterministic membership values. This difference becomes especially important under peak-hour congestion, demand imbalance, irregular arrivals, weather disturbance, and other conditions that make traffic states highly variable.

Table 2. Synthesis of Selected Studies on Type-2 Fuzzy Logic for Signalized Intersections

Author (s) and year	Research focus	Traffic condition / assumption	Main quantitative finding	Computational / implementation note	Relevance to the present study
Korkmaz and Akgüngör (2024)	Hybrid traffic controller based on FL-T2 optimized by Crow Search Algorithm	Adaptive control under fluctuating traffic demand	Approximately 32% better performance than fixed-time control and 5%–6% better than Type-1 fuzzy control in delay reduction	Hybrid optimization improved performance but increased tuning complexity	Confirms that FL-T2 is most effective when traffic demand is highly dynamic
Jovanović et al. (2023)	Interval Type-2 fuzzy control for RCUT intersections	Unconventional intersection geometry and variable flow patterns	Better queue length control and fewer stops than alternative control modes	Suitable for complex layouts, but implementation depends on reliable input data	Supports the use of FL-T2 in non-standard intersection configurations
Shao et al. (2024)	Dual-layer adaptive signal timing framework	Simulation-based validation	Delay reduction ranging from	Learning layer improved responsiveness, but	Demonstrates the benefit of combining FL-T2 with

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Author (s) and year	Research focus	Traffic condition / assumption	Main quantitative finding	Computational / implementation note	Relevance to the present study
	with fuzzy-based learning	under changing traffic volumes	11.1% to 29.0%	computational burden was higher than basic fuzzy control	adaptive learning
Bi et al. (2024)	Integration of FL-T2 with Deep Q-Network	Intelligent adaptive control in variable traffic environments	Improved learning performance and enhanced traffic flow efficiency	Strong performance, but architecture is more complex and less transparent	Indicates future potential through hybrid intelligent control
Arteaga et al. (2022)	Adaptive fuzzy controller with lower computational demand	Resource-limited or lower-complexity environments	Competitive performance with simpler technical requirements	Lower computational burden makes implementation more feasible	Suggests a practical option when computing resources are limited
Chala and Kóczy (2024)	Fuzzy rule-base reduction for complex intersections	Complex intersection control with many decision rules	Rule reduction improved efficiency without major performance loss	Reduced complexity and easier real-time use	Relevant for making FL-T2 more deployable in practice

Source: Data Research 2026

Table 2 shows that stronger performance is often reported in studies that combine FL-T2 with optimization or learning-based enhancement. For example, hybrid controllers optimized through metaheuristic algorithms or reinforcement learning tend to achieve larger delay reductions and better responsiveness than standalone fuzzy controllers. This suggests that FL-T2 is not only a control architecture but also a flexible framework whose effectiveness increases when parameter tuning is supported by computational intelligence methods. However, this also means that the observed improvement cannot be attributed to FL-T2 alone; in many cases, part of the gain comes from the optimization layer, which increases the complexity of interpretation and implementation.

The comparative evidence also suggests that FL-T2 is most effective under dynamic, uncertain, and non-uniform traffic conditions. Its advantage is less pronounced in stable low-volume environments where fixed-time control may already provide adequate performance with lower computational cost. In other words, FL-T2 is best understood as a high-value solution for intersections with volatile demand, frequent queue formation, and noisy or incomplete detector input. Under such conditions, the ability of FL-T2 to preserve decision stability while accommodating uncertainty becomes its main technical advantage.

At the same time, the reviewed literature does not present FL-T2 as a cost-free solution. The use of upper and lower membership functions, the type-reduction stage, and the need for careful calibration increase the computational burden relative to simpler control approaches. For this reason, studies that report strong performance often do so in simulation environments, where processing constraints are less restrictive than in field deployment. Future implementations therefore need to balance performance gains against computational feasibility, especially if real-time operation is required at busy urban intersections.

Taken together, Table 2 suggests that FL-T2 is most convincing when evaluated not simply by whether it "performs better," but by under what conditions it performs better, what additional algorithms support that performance, and what implementation trade-offs are introduced. This more contextual reading is essential for a review paper because it avoids overstating the superiority of one method while ignoring the assumptions under which the reported gains were obtained.

3.3. Effects on Delay, Queue Length, and Degree of Saturation

The synthesis of selected studies indicates that FL-T2 has a consistent positive effect on three core performance indicators of signalized intersections: average delay, queue length, and degree of saturation. As summarized in Table 3, delay reduction is the most frequently reported benefit, mainly because FL-T2 can adjust green time dynamically in response to real-time traffic variation. This makes the controller more responsive than fixed-time systems, which cannot react quickly to sudden surges in demand or imbalance between approaches.

Table 3. Comparative Effects of FL-T2 on Key Intersection Performance Indicators

Performance indicator	Condition under fixed-time or conventional control	Effect of FL-T2 implementation	Supporting interpretation	Limitations / caveats
Average delay	Higher delay is common because signal timing is static and less responsive to traffic fluctuations	Delay is reduced through adaptive green-time adjustment	FL-T2 improves time efficiency especially under volatile demand and peak-hour imbalance	Benefits are smaller in stable low-volume traffic where fixed-time control may already be adequate
Queue length	Queues tend to accumulate during peak periods or imbalanced demand conditions	Queue length is reduced through dynamic response to volume and queue variation	FL-T2 better redistributes service time across approaches, preventing spillback	Performance depends on accurate and timely detector input

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Performance indicator	Condition under fixed-time or conventional control	Effect of FL-T2 implementation	Supporting interpretation	Limitations / caveats
Degree of saturation	Saturation is more likely to exceed desirable limits under rapidly changing traffic conditions	Saturation is kept closer to acceptable operating limits	FL-T2 increases intersection stability under uncertain demand	Gains may diminish if the controller is poorly tuned or input data are noisy
System flexibility	Decisions are based on fixed historical assumptions, so adaptability is limited	Flexibility is high because uncertainty is explicitly handled through FOU and adaptive inference	FL-T2 is more suitable for dynamic urban traffic environments	Higher flexibility comes with greater computational and calibration complexity
Computational cost	Typicaly lower for fixed-time or Type-1 control	Generally higher due to upper/lower membership functions and type-reduction	More capable of uncertainty handling, but not always the most economical option	Real-time deployment may require optimization, rule reduction, or hardware support

Source: Data Research 2026

Queue length shows a similar pattern. FL-T2 helps distribute service time more proportionally across competing traffic streams, reducing the likelihood of long vehicle queues accumulating on critical approaches. This is particularly useful in conditions where arrival rates fluctuate sharply, since static timing often creates unnecessary delay in one approach while another approach remains under-served. The literature therefore suggests that queue reduction is not merely a side effect of FL-T2, but a direct consequence of its ability to adapt phase duration to changing field conditions.

Degree of saturation is also improved because FL-T2 tends to keep the intersection closer to a more stable operational balance. However, this result should not be interpreted as universally guaranteed. The effect depends on the quality of the input data, the accuracy of the rule base, and the responsiveness of the control cycle. Where detector coverage is poor or traffic measurements are delayed, the practical benefit may weaken. This indicates that FL-T2 is effective primarily when the system has access to timely and reasonably reliable traffic information.

The table also highlights an important trade-off: greater flexibility usually comes with greater computational complexity. Compared with fixed-time or basic Type-1 control, FL-T2 requires more processing because of the additional uncertainty modeling and type-reduction steps. In a simulation environment, this cost is often acceptable; in a real intersection controller, however, the designer must ensure that the algorithm remains fast enough for real-time operation. Consequently, the practical value of FL-T2 lies not only in its performance improvement, but also in whether that improvement can be delivered within the limits of local infrastructure and hardware capacity.

From a review perspective, the key point is that FL-T2 should not be described merely as "better" than conventional control. A more accurate interpretation is that FL-T2 is more suitable for uncertain and rapidly changing traffic environments, particularly when the goal is to reduce delay and prevent queue buildup without sacrificing operational stability. This interpretation is more defensible because it links performance outcomes to operating conditions, implementation assumptions, and computational trade-offs rather than treating the reported improvements as context-free facts.

3.4. Relevance to Indonesian Traffic Conditions

The application of FL-T2 is particularly relevant for Indonesian urban traffic conditions because many intersections still face fluctuating demand, heterogeneous vehicle composition, and recurring peak-hour congestion. In principle, these characteristics make Indonesian intersections well suited to an adaptive controller that can explicitly handle uncertainty. However, practical implementation cannot be assumed to be straightforward, because traffic signal control in Indonesia is not uniform across cities and districts, and the availability of sensing infrastructure varies considerably. Some urban areas already use camera-based or coordinated adaptive systems, while others still rely heavily on fixed-time operation or limited local adjustments.

A major factor affecting the feasibility of FL-T2 is the availability and reliability of traffic detectors. Several Indonesian intersections have begun to use CCTV-based monitoring or detector-assisted traffic management, indicating that the technical foundation for adaptive control already exists in some locations. At the same time, broader deployment remains constrained by uneven detector coverage, incomplete real-time data collection, and differences in maintenance capacity between cities. For FL-T2, this matters because the controller depends on timely and reasonably accurate input variables such as queue length, arrival rate, and vehicle volume. If these data are delayed or noisy beyond acceptable limits, the expected performance gains may be reduced.

The institutional readiness for advanced adaptive control is also an important issue. Although some Indonesian cities have implemented traffic management technologies, the transition from monitoring-based systems to fully adaptive decision-making requires coordination among transportation agencies, local governments, and system operators. In addition, FL-T2 deployment would likely require calibration using local traffic patterns, which differ across metropolitan, medium-sized, and rapidly growing urban areas. This means that a controller designed from international datasets cannot simply be transferred without adjustment. The reviewed literature therefore supports the need for local simulation studies followed by pilot-scale validation in selected Indonesian intersections.

Cost is another practical consideration. A high-performing FL-T2 system may require detectors, computing resources, integration with control hardware, and periodic recalibration. These requirements can be manageable in intersections with existing intelligent transportation infrastructure, but they may be difficult to justify in resource-limited locations if the performance gain over simpler methods is not substantial enough. For this reason, the most realistic implementation pathway in Indonesia is likely to begin with high-congestion corridors or pilot intersections that already have monitoring support. Such a staged approach would allow the performance, maintenance burden, and operational value of FL-T2 to be evaluated before wider deployment.

Overall, the reviewed evidence suggests that FL-T2 is promising for Indonesian traffic control, but its adoption should be framed as a gradual and context-dependent process rather than an immediate universal solution. Its strongest application potential lies in intersections with highly variable traffic, existing sensing support, and institutional readiness for adaptive control. Future studies should therefore prioritize local data collection, simulation using Indonesian traffic patterns, and field trials that consider not only delay and queue performance, but also infrastructure cost, maintenance feasibility, and operational integration with existing signal control systems.

3.5. Future Improvements

The literature suggests several promising directions for improving FL-T2-based signal control. First, hybridization with optimization algorithms can help calibrate membership functions and reduce manual tuning effort. Second, integration with machine learning or reinforcement learning may improve adaptability under highly variable demand patterns. Third, rule-base reduction may help lower computational cost without sacrificing too much accuracy.

For future work, the most important step is to move beyond simulation-only validation and test FL-T2 using measured local traffic data from Indonesian intersections. Such studies would provide stronger evidence of feasibility, help identify context-specific parameter settings, and clarify whether the performance gains reported in the international literature are transferable to local traffic environments.

Table 4. Summary of Main Conclusions and Research Implications

Main conclusion	Supporting explanation	Research implication
FL-T2 is more effective than fixed-time and Type-1 fuzzy control under dynamic traffic conditions	It accommodates uncertainty in traffic data more effectively, especially when demand is fluctuating, arrivals are irregular, and detector input is noisy	FL-T2 is suitable as a conceptual basis for adaptive signal control in uncertain urban intersections
The FL-T2 architecture is built on four core components	Fuzzification, rule base, inference, type-reduction, and defuzzification work together to produce adaptive signal decisions	The framework can be used as a structured reference for future controller design
The Footprint of Uncertainty is the key technical advantage of FL-T2	It represents layered ambiguity in real traffic variables and supports more stable decision-making	More realistic uncertainty handling can improve signal timing robustness

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Main conclusion	Supporting explanation	Research implication
FL-T2 has practical relevance for Indonesian urban intersections, but its adoption is context-dependent	Local traffic conditions are variable, but detector availability, data quality, and institutional readiness still differ across cities	Local simulation and staged pilot implementation should be prioritized before wider deployment
Hybrid optimization and intelligent learning are promising future directions	Additional algorithms can improve membership calibration and reduce manual tuning effort, but they also increase computational complexity	Future FL-T2 research should balance performance gains with implementation efficiency

Source: Data Research 2026

4. Conclusion

This review indicates that Type-2 Fuzzy Logic is a promising adaptive control approach for signalized intersections under uncertain traffic conditions. Compared with fixed-time control and Type-1 fuzzy logic, FL-T2 offers stronger capacity to represent traffic uncertainty through the Footprint of Uncertainty, which makes it particularly suitable for intersections with fluctuating demand, noisy detector input, and non-uniform congestion patterns. The reviewed studies also show that FL-T2 can contribute to lower delay, shorter queues, and more stable degrees of saturation, especially when it is supported by optimization or learning-based enhancement.

At the same time, the review shows that FL-T2 should not be treated as a universal solution. Its effectiveness depends on the quality of traffic data, the structure of the rule base, the computational load of the controller, and the readiness of the local traffic management environment. These factors are especially important in Indonesia, where detector availability, data consistency, and infrastructure readiness vary across cities and intersections. For this reason, the most realistic path forward is staged implementation through simulation, pilot testing, and local calibration before wider deployment.

Future research should therefore move beyond conceptual discussion and focus on local validation using Indonesian traffic data. Priority should be given to studies that examine performance under real operating conditions, assess implementation cost, and test hybrid FL-T2 models that combine fuzzy control with optimization or intelligent learning methods. Such work would not only strengthen the scientific basis of FL-T2, but also clarify its practical value for adaptive traffic signal control in Indonesian urban settings.

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