ILLINOIS CENTER FOR TRANSPORTATION

Report No. FHWA-ICT-25-005

State Department of Transportation Support for Operationalizing Transit Signal Priority

Abolfazl (Kouros) Mohammadian
Mohammad Miralinaghi
Alireza Talebpour
Sajad Askari
Sanaz Kazemzadehazad

ICT Project R27-259

June 2025

ISSN: 0197-9191
ICT Series Report No. 25-005
https://doi.org/10.36501/0197-9191/25-005

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-ICT-25-005	N/A	N/A

4. Title and Subtitle	5. Report Date
State Department of Transportation Support for Operationalizing Transit Signal Priority	June 2025
	6. Performing Organization Code
	N/A
7. Authors	**8. Performing Organization Report No.**
Abolfazl Mohammadian, http://orcid.org/0000-0003-3595-3664 Mohammad Miralinaghi, https://orcid.org/0000-0002-4547-4192 Alireza Talebpour, https://orcid.org/0000-0002-5412-5592 Sajad Askari, https://orcid.org/0000-0003-3121-8558 Sanaz Kazemzadehazad, https://orcid.org/0000-0002-1382-8451	ICT-25-005 UILU-2025-2005
9. Performing Organization Name and Address	**10. Work Unit No.**
Illinois Center for Transportation Department of Civil and Environmental Engineering University of Illinois Urbana-Champaign 205 North Mathews Avenue, MC-250 Urbana, IL 61801	N/A **11. Contract or Grant No.** R27-259
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Illinois Department of Transportation (SPR) Bureau of Research 126 East Ash Street, Springfield, IL 62704	Final Report 7/1/23–6/30/25 **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

https://doi.org/10.36501/0197-9191/25-005

16. Abstract

Transit signal priority (TSP) systems have become an integral part of regional intelligent transportation systems integration. They modify signal operations to facilitate faster transit through intersections, improve transit service reliability, reduce delays, and enhance overall transit operational efficiency. Agencies are planning and implementing next-generation TSP systems. However, multifaceted challenges complicate TSP implementation, particularly in urban regions with high traffic density and multiple stakeholders. Exploring these challenges can help develop more efficient deployment strategies and improve system performance. This study's researchers, therefore, examined TSP implementation challenges in the metropolitan Chicago area and interviewed stakeholders and experts from Illinois and other states to identify successes and obstacles in TSP deployment. They applied a thematic analysis and a non-negative matrix factorization method to identify key barriers. To prioritize these challenges, they developed a survey using the fuzzy analytic hierarchy process framework and had experts directly involved in TSP operations in the Chicago region participate in this survey. Study findings indicated that organizational factors—such as interagency coordination issues and labor shortages—are significant challenges. Regulatory and policy constraints, including the absence of standardized regional guidelines and concerns over equipment compatibility, further hinder TSP deployment. Financial constraints, particularly the reliance on fragmented funding sources, create uncertainty in project execution. Technological limitations, such as integration difficulties with legacy traffic control systems and the high costs of infrastructure upgrades, also impede implementation.

17. Key Words	18. Distribution Statement
Traffic Signal Priority, Deployment Challenges, Implementation Barriers, Interagency Coordination Issues, Regulatory Constraints	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	28	N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-259: State Department of Transportation Support for Operationalizing Transit Signal Priority**. ICT-R27-259 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review Panel (TRP) were the following:

- Charles Abraham, TRP Co-Chair, Illinois Department of Transportation
- Taqhi Mohammed, TRP Co-Chair, Pace Suburban Bus
- Hugo Coronado, Metropolitan Planning Council
- Shane Cullen, Illinois Department of Transportation
- Julia Hage, Center for Neighborhood Technology
- Mark Kane, Federal Highway Administration
- Kamil Kobylka, Illinois Department of Transportation
- Martin Menninger, Chicago Metropolitan Agency for Planning
- Angela Ng, Chicago Transit Authority
- Mark Pitstick, Regional Transportation Authority
- Matt Pitts, Chicago Department of Transportation
- Alex Rivera, Illinois Department of Transportation
- Todd Schmidt, Chicago Metropolitan Agency for Planning

EXECUTIVE SUMMARY

This study's research team explored transit signal priority (TSP) implementation challenges in metropolitan Chicago. They primarily sought to identify key barriers to TSP implementation and to develop recommendations for improving interagency coordination, regulatory compliance, funding strategies, and technological integration. To achieve these objectives, they interviewed experts from state transportation agencies, transit authorities, and planning organizations as well as reviewed best practices from regions where TSP had been successfully deployed. They applied thematic analysis and topic modeling techniques to their collected data to extract the barriers affecting TSP implementation. They used the fuzzy analytical hierarchy process to assign priority weights to the identified challenges.

The findings revealed that organizational factors pose the most significant challenges to TSP implementation. Staff turnover and labor shortages have added to lengthy and complex permit approval processes and further delayed progress. Interagency operability issues and inconsistent access to technical tools have created additional complexities when coordinating among transit providers, traffic control agencies, and municipal authorities. Regulatory and policy constraints have also added implementation difficulties. Funding limitations have further complicated TSP implementation. High infrastructure costs have created uncertainty in project planning and execution. Budget allocation and prioritization challenges have meant that agencies struggle to secure consistent financial support for upgrading signal infrastructure and maintaining TSP systems. Financial constraints have also limited the ability to expand centralized traffic management solutions, further exacerbating coordination difficulties.

Technical and technological factors have played a key role in determining TSP efficiency. Integrating TSP with existing infrastructure has been challenging, as older traffic control systems often require significant modifications to accommodate priority signaling. The complexity of TSP systems, particularly in decentralized environments, have hindered the scalability of implementation. Additionally, transitioning to centralized or cloud-based traffic management systems have required substantial investment in hardware and software upgrades.

This study's analysis highlights several actionable recommendations. Streamlining business processes for permit approvals and engineering reviews would reduce implementation delays. Establishing a dedicated oversight entity for TSP development would improve coordination across multiple agencies, ensuring that projects progress efficiently. Expanding financial support through dedicated TSP funding streams would address the resource gaps that transit agencies face. Moreover, investing in a centralized control system and in traffic management tools would enhance the accuracy of system optimization and improve decision-making processes.

Addressing barriers to TSP implementation requires a comprehensive strategy that encompasses regulatory streamlining, financial planning, interagency collaboration, and technological modernization. State departments of transportation can adopt these measures to enhance transit efficiency, reduce travel delays, and improve overall urban mobility through successful TSP deployment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Improving transit service is one of the most effective strategies for mitigating such negative impacts of car dependency as fuel consumption and pollutant emissions. However, in many major American cities buses frequently compete with other roadway users at intersections, often resulting in significant delays. Public transit delays can significantly impact various aspects of transit system operations, including increased travel and waiting times for passengers, reliability issues (such as reduced punctuality, fluctuating intervals, and bus bunching), higher operational costs, and increased emissions. Therefore, urban transportation authorities have shifted their attention toward transit-oriented design to reduce transit delays, which can broadly benefit passengers and service providers (and potentially, other roadway users). Traffic signals are a major contributor to transit delays (Shalaby et al., 2021). In this regard, one of the key innovations of transportation systems management and operations to mitigate transit delay is bus transit signal priority (TSP) (Anderson et al., 2020).

TSP is a technology that adjusts the start and end times of traffic control signal phases and the sequence of phases (Shalaby et al., 2021) to give priority to transit buses if specific conditions are met. TSP considerably improves bus service reliability (Anderson & Daganzo, 2020), reduces delays (Shalaby et al., 2021), and promotes operational efficiency (Wu & Guler, 2019). In the transit signal priority handbook, for example, Smith and colleagues (2005) mentioned that TSP combined with signal optimization reduced transit signal delays by approximately 40% along two major corridors in Tacoma, Washington. In Portland, Oregon, TriMet experienced a 10% improvement in travel time and up to a 19% reduction in travel time variability. TriMet, therefore, could avoid adding an additional bus and reduce scheduled recovery time, given increased reliability. In Chicago, Pace buses achieved an average running time reduction of 15%, which corresponds to approximately three minutes, with actual reductions varying between 7% and 20%, depending on the time of day. Pace also realized cost savings equivalent to one weekday bus while maintaining the same service frequency through more efficient TSP use and run cutting. Similarly, in Los Angeles, TSP implementation led to reductions in bus travel times of up to 25%, demonstrating its effectiveness in large urban environments.

Based on the New York City Department of Transportation (NYC DOT), TSP implementation in New York City has consistently resulted in significant reductions in bus travel times. Since 2012, the NYC DOT and the Metropolitan Transportation Authority have implemented TSP across five corridors, leading to an average reduction in bus travel times of approximately 14% during weekday peak travel periods. The results varied across different corridors, directions, and times of day, with travel time savings ranging from less than 1% to up to 25% (NYC DOT, 2018).

TSP involves four main components (Baker et al., 2002): (1) a detection system that locates the vehicle requesting priority, (2) a priority request generator that alerts the traffic control system, (3) software for deciding whether and how to grant priority based on preprogrammed control strategies, and (4) management software that collects data and generates reports. It is important to note that TSP differs from signal preemption. Signal preemption modifies normal signal operations for special events such as emergency vehicle responses, while TSP only optimizes the signal process to better accommodate transit vehicles. Various TSP implementation methods include passive priority, early green (red truncation), green extension, actuated transit phases, phase insertion, and adaptive or real-time control (Baker et al., 2002). These implementations can occur either locally, where the bus directly interacts with signal controllers, or at the network level, where bus location data are used to determine selective priority.

TSP has gained increasing attention since the late 1960s and has been successfully implemented in many cities worldwide. The growing diversity and complexity of TSP system architecture and business rules, as well as their different implementation strategies (planning, design, implementation, operation, and maintenance), may lead to complicated coordination challenges among various stakeholders. To best address these coordination challenges in Illinois, the research team investigated and studied existing TSP implementations in various states, catalogued each involved entity's responsibilities and business procedures, identified best practices, and customized an appropriate strategy to address specific operational issues. They built upon work published by Smith et al. (2005). Unfortunately, despite multiple studies on TSP implementation strategies, there is still a scarcity of literature related to the business rules and parameters that are commonly employed in practice.

Effective collaboration among stakeholders is essential for overcoming the technical, financial, and regulatory challenges associated with TSP implementation. Figure 1 presents the TSP implementation process and highlights the key stakeholders involved in the operation of this system. The central flowchart in Figure 1 illustrates the primary stages of TSP deployment: planning, design, implementation, operations/maintenance, and evaluation. Surrounding the flowchart are various stakeholder groups that play a critical role in the TSP process, including key government agencies such as the U.S. Department of Transportation, the Federal Highway Administration, the Federal Transit Administration, state DOTs, municipalities, and metropolitan planning organizations (MPOs). Additionally, transit agencies, signal operators, private vendors, emergency service providers, university research centers, and public officials are actively involved in the TSP process. Each stakeholder's role can vary depending on the context. In areas with overlapping jurisdictions across multiple government districts, stakeholder contributions can become complex. Organizational collaboration, therefore, plays a significant role in ensuring the successful implementation and operation of TSP systems.

The key stakeholders in TSP implementations, besides roadway users, are the departments of transportation, transit agencies, municipalities, counties, and vendors that federal and/or local funding agencies support. The local funding agencies include state DOT grants and programs, state transit assistance funds, state-matching funds, and MPO funding. Transit agencies, as the main executive entity, design bus routes and schedules in their planning department based on various factors (including travel time and accessibility) and adjust service plans based on TSP performance data. They also equip transit vehicles with the necessary hardware and software to communicate with traffic signals and should monitor the performance of TSP systems and submit their reports to the funding agencies. DOTs are responsible for establishing policies, guidelines, and standards for TSP implementation to ensure consistency and interoperability across jurisdictions.

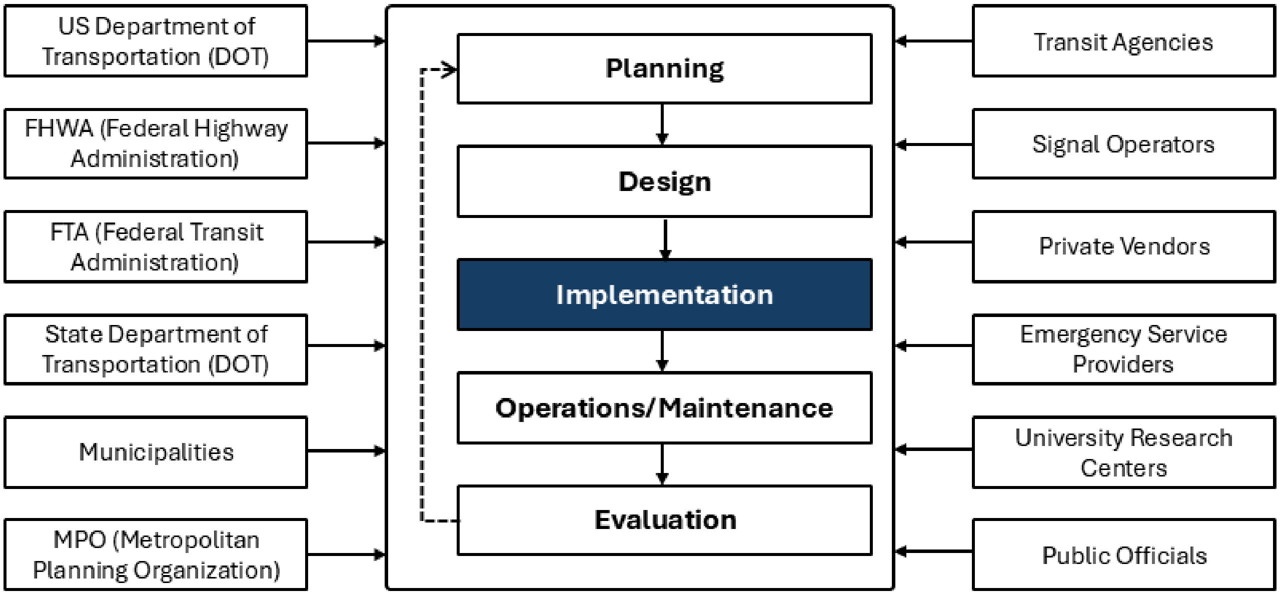


Figure 1. Flowchart. Process and stakeholders involved in TSP deployment.

Source: Adapted from Baker et al. (2002)

DOTs are responsible for upgrading roadway infrastructure. They oversee the upgrade and maintenance of traffic signal infrastructure to accommodate TSP technologies, including installing or upgrading signal controllers and communication networks. DOTs usually hold the leadership role, facilitate coordination between different agencies, and ensure the integration of TSP with other traffic management systems. Funding agencies, such as federal agencies, MPOs, and local governments, provide the necessary financial resources for TSP projects. They manage and distribute grant funds, ensuring that projects meet eligibility criteria and comply with funding requirements. Municipalities and counties are responsible for locally implementing TSP in their territory, including adjusting traffic signal timing and maintaining signal equipment. They coordinate with transit agencies and DOTs to ensure seamless TSP operations within their jurisdiction. Vendors supply the hardware and software solutions required for TSP, including on-board equipment for transit vehicles and signal controllers for intersections. They ensure that TSP systems are integrated with existing traffic management and transit operations systems. In some states, they are responsible for providing technical support, upgrading TSP technologies, and providing maintenance services to ensure TSP system reliability and performance.

Despite TSP's well-documented benefits, various challenges exist in its implementation, which can extend project timelines for years. Although numerous studies have examined different aspects of TSP, the literature has overlooked TSP implementation barriers. In this report, the research team investigated challenges that complicate or hinder TSP implementation in metropolitan Chicago. The research team first conducted interviews with experts and stakeholders, identified the most significant challenges, and ultimately pinpointed primary barriers.

CHAPTER 2: BACKGROUND

This section provides a two-part brief overview of different studies on TSP implementation. The first part briefly investigates TSP strategies. The second part presents examples of business practices involved in adopting TSP in states that have already implemented it. This review provides insight into the current state of practice, performance, and challenges of different agencies across the United States. The research team later used this information to design a questionnaire for interviewing agencies in greater detail and for supporting transit signal priority implementation in Illinois.

TSP literature is heavily focused on TSP operating strategies. There are two traditional TSP strategies: active and passive. Passive TSP is implemented offline using historical transit routes and ridership data. This method works well with consistent and frequent bus arrival patterns. In most cases, this treatment causes unnecessary or even excessive delays for conflicting traffic. Active priority, on the other hand, recognizes approaching transit vehicles at signalized intersections and dynamically alters signal timing in response to approaching transit vehicles.

Despite numerous resources for various TSP strategies, the literature on TSP business processes is scarce. Therefore, the research team obtained information on several states' TSP implementation processes from agency websites, handbooks, and interview-based research.

Table 1 synthesizes several studies on TSP implementation in the United States, including each agency's TSP implementation status, strategy, and measure of effectiveness (MOE), followed by references to business procedure examples of states that implemented TSP.

In Northeastern Illinois, the Chicago Department of Transportation (CDOT) and the Chicago Transit Authority (CTA) primarily manage the City of Chicago's TSP infrastructure. The Illinois Department of Transportation (IDOT) and Pace serve Chicago's suburbs. The Regional TSP Implementation Program implements the TSP system's integral component in metropolitan Chicago. This program covers around 500 intersections across different jurisdictions. Several partners collaborate in this program, such as the Regional Transportation Authority (RTA), CTA, Pace, IDOT, and CDOT (RTA, 2019).

Table 1. A Summary of TSP Case Studies

City/State/University	Approach	Situation	Strategy	Condition	MOEs
Portland, Oregon	Empirical TSP	Implemented	N/A	TSP granted to buses that are behind schedule	−0.30% (average bus travel time)
Provo and Orem, Utah	Empirical TSP	Implemented	Phase Extension, Red Truncation	TSP can be requested within a two-minute window for each bus	No data
Nashville, Tennessee	Simulation Theoretical Evaluation	Phase Extension, Red Truncation	Unconditional	Up to 14.4% (reduction in bus delay), −4.5% (increase in side street delay)	
Moorhead, Minnesota/Fargo, North Dakota	Simulation Theoretical Evaluation	Phase Extension, Red Truncation	Unconditional	Up to 14% (reduction in delay), 24.42% (increase in side street delay)	
Orlando, Florida	Simulation TSP Implemented	Phase Extension, Red Truncation	TSP granted to buses a few minutes behind schedule	−5% (bus travel time), −23% (average delay)	
Michigan State University Campus	Simulation Theoretical Evaluation	Phase Extension, Red Truncation	TSP granted if the bus can pass intersection within the extended green time, with red truncated	−14% (side street delay), 2% (improvement in schedule adherence)	
Burlington, Vermont	Simulation Theoretical Evaluation	Phase Extension	Unconditional	2%–7% (improvement in bus travel time), negligible (side street delay)	
Harvey, Illinois	Actual Evaluation	TSP Implemented	Conditional	Up to 15	
Snohomish County, Washington	Empirical, Simulation	TSP Implemented	Phase Extension, Red Truncation	TSP granted to buses that are behind schedule	−3% (bus travel time), +1% (side street delay)

Vlachou et al. (2010) conducted a comprehensive study of business processes for TSP implementation in small- and medium-sized cities. San Diego Metropolitan Transit System's TSP design and implementation has successfully involved several other agencies such as Caltrans, the Cities of San Diego and Chula Vista, the IBI Group, and the San Diego Association of Governments. Caltrans' signals follow a passive TSP, but Caltrans has plans to implement TSP at ramp meters in the future. The San Diego Metropolitan Transit System is responsible for TSP hardware on transit buses, while the Cities of San Diego and Chula Vista install and maintain this system at their own traffic signals. The IBI Group, a consulting firm, helps cities with traffic signal operations and maintenance planning. The San Diego Metropolitan Transit System encountered some challenges in practice, such as continued TSP operation and performance deterioration because of bugs, unforeseen problems, and changing traffic conditions, and engaged IBI Group on a monitoring contract. The San Diego Metropolitan Transit System and IBI Group have encountered problems over time, including signal software losing coordination, skipping side streets and pedestrian calls, and an update to bus announcements disrupting the infrared emitters. The IBI Group, as a monitoring contractor, has addressed these challenges, updating parameters based on observations of field data. The San Diego Association of Governments coordinates each of the aforementioned entities.

The Rhode Island Public Transit Authority has three TSP implementation partners, including the Rhode Island Department of Transportation and the Cities of Pawtucket and Providence. The Rhode Island Public Transit Authority is responsible for installing, operating, and maintaining TSP software and hardware on buses. Like the San Diego Metropolitan Transit System, the Rhode Island Department of Transportation and the Cities of Pawtucket and Providence are responsible for installing and maintaining their own TSP equipment. The Rhode Island Public Transit Authority's planning department operates and monitors the TSP system. Their most challenging task is coordinating with their TSP implementation partners over maintenance.

The San Francisco Municipal Transportation Agency is implementing TSP with a simple administrative structure. They are responsible for the entire process because they have their own transit fleet and traffic signals. They have a division, the Sustainable Streets Division, which is responsible for operating and maintaining traffic signals. This division is also responsible for the TSP-associated hardware installed at intersections. However, they have difficulty identifying the sources of anomalies in their system, whether originating from a bus or intersection hardware. It is thus easier to secure funding for new intersections than maintaining existing intersections (Vlachou et al., 2010).

The Massachusetts Bay Transportation Authority (MBTA), in collaboration with local traffic signal owner-operating agencies, operates a TSP system to enhance on-time performance and operational efficiency of its transit services in the greater Boston area. TSP is a crucial strategy for improving reliability and speed of MBTA bus and light rail services, thereby making public transportation a more viable and attractive option for commuters. The current state of TSP in MBTA (as a division of the Massachusetts Department of Transportation) is a centralized system that covers 26 corridors in a five- to seven-year implementation period, with a target of improving equity and minimizing existing delays to meet Massachusetts Department of Transportation goals (MBTA, 2024).

A few studies have also investigated TSP implementation challenges. TCRP Report 149 (Anderson et al., 2020) highlighted TSP implementation challenges, including gaining early-stage stakeholder buy-in, since local community resistance can be significant, and ensuring ongoing maintenance and troubleshooting, given potential system failures from software updates. Political and operational challenges, such as changes in priorities and governance structures, complicate deployment, while technological limitations like GPS disruptions in urban areas pose additional hurdles. Quantifying TSP benefits is difficult without baseline data. Other transit improvements can also confound quantifying TSP benefits. Effective coordination with jurisdictions managing traffic signals and ensuring system reliability are critical but often challenging. Adapting to system changes, maintaining long-term operations under budget pressures, and determining optimal business rules and parameters require continuous effort and reevaluation to maximize TSP benefits.

Baker et al. (2002) identified the following key issues when planning for TSP systems. First, defining stakeholder roles and responsibilities early in the planning phase is crucial since it helps build strong interagency relationships and ensures regional management and coordination of TSP issues. Second, the complexity of integrating TSP with other intelligent transportation systems and ensuring compatibility with existing traffic signal hardware and software poses significant challenges. Third, detailed data collection and inventory of traffic control systems are necessary, followed by a comprehensive design and engineering phase that considers roadway geometry, traffic volumes, transit stop locations, and pedestrian impacts. Fourth, securing funding and maintaining the system can be problematic since TSP requires ongoing performance monitoring, management, and technical support for field equipment installation. Fifth, effective communication and cooperation between transit and traffic agencies are vital since different professional terminologies and operational priorities can hinder the planning process.

Smith et al. (2005) stated that ensuring consistency with regional and corporate goals is essential since isolated projects can disrupt the broader transportation system. Early identification and stakeholder involvement, both internal and external to the transit agency, is vital to gaining support and avoiding roadblocks. Establishing a strong partnership between transit and traffic management agencies is crucial since these projects often represent the first collaboration among these agencies. Clear communication and defined roles and responsibilities among stakeholders help manage expectations and streamline the process. Additionally, TSP projects require a comprehensive needs assessment to evaluate potential benefits, feasibility, costs, and a return-on-investment analysis. This assessment must address the impact of traffic signal delays on transit travel times and reliability. Effective project management is necessary to coordinate the multiple jurisdictions and agencies involved, with clear communication strategies and interagency agreements. Finally, the technical aspect of planning involves a detailed design and engineering process, including data collection, signal timing optimization, and, potentially, the use of simulation models for special assessments.

Shalaby et al. (2006) outlined several implementation challenges for TSP systems. A primary challenge is integrating TSP with existing traffic systems to ensure that it does not adversely impact overall traffic flow and other vehicle types. Technological requirements also present significant challenges since advanced and reliable automated vehicle location and automated passenger counting systems are necessary for real-time data collection and implementation of sophisticated algorithms for accurate transit travel time prediction and adaptive signal control. Another critical issue is the development of conditions for granting TSP, such as schedule adherence and vehicle occupancy, to avoid unnecessary signal priority and prevent traffic disruptions. The cost and feasibility of deploying these systems, particularly the high costs associated with traffic sensors and other infrastructure, also pose substantial challenges. This is especially true in areas with lower traffic volumes or smaller municipalities, where the benefits might not justify the expense. Additionally, building consensus among various stakeholders, including traffic and transit agencies, is essential for successfully designing and implementing TSP systems.

CHAPTER 3: DATA COLLECTION AND METHODS

This chapter presents an overview of the research team's data collection efforts as well as the various methods they used to collect data.

DATA COLLECTION

To identify TSP implementation challenges and opportunities as well as develop state-level policy and regulatory recommendations consistent with federal rules, regulations, and state statutes, the research team collected data through stakeholder interviews in two steps. They first interviewed Illinois and out-of-state staff and stakeholders. These interviews lasted between 45 to 60 minutes. They were conducted via Zoom and audio recorded with interviewees' permission. They identified Illinois agencies responsible for TSP implementation through this process and scheduled meetings with their respective staff members. They designed a detailed questionnaire to guide discussions during the hour-long meetings, covering various aspects of TSP implementation. During the meetings, agency representatives shared insights and experiences related to TSP implementation, addressing project objectives, challenges, technological solutions, and lessons learned. The research team then prepared detailed minutes to document the key points discussed.

They repeated this process for out-of-state agencies with successful TSP implementation, following the same steps of identification, scheduling, questionnaire design, interviews, and minute taking. The interviews with out-of-state agencies were similar to those of the state agencies. However, there were some additional questions regarding their best practices and the solutions in which they had addressed their challenges. Overall, the interview process served as a valuable means of gathering firsthand knowledge and experiences, informing an understanding of best practices and challenges associated with TSP projects.

Selection of Agencies and Participants

The research team attended several coordination and kickoff meetings with Illinois stakeholders and reviewed literature and guidelines for best practices regarding TSP operations. These stakeholders are listed below:

1. In the State of Illinois: The main stakeholders include RTA, CTA, Pace, CDOT, IDOT, and the Chicago Metropolitan Agency for Planning, as shown in Figure 2, with the support of the Metropolitan Planning Council (MPC) and the Center for Neighborhood Technology (CNT).

2. Out-of-State Agencies: These agencies included the DOTs of the San Francisco Municipal Transportation Agency as a combined transit agency and DOT, the NYC DOT, and transit agencies of the Massachusetts Bay Transportation Authority, the Rhode Island Public Transit Authority, and Metro.

Description of the Questionnaire

The research team used these interviews to understand the current state of (i) stakeholders' responsibilities and involvement, ranging from communication equipment installation to TSP control strategy design; (ii) stakeholder communications; (iii) jurisdictional partnerships for project coordination; and (iv) TSP implementation standards and guidelines development. They developed a distinct questionnaire for state DOT representatives, another for transit agencies, and another for other planning centers that have a supporting role (MPC and CNT) (see Figures 2–4) with the aim of gathering comprehensive insights into TSP implementation. They designed the questionnaires to focus on details about various aspects of TSP projects, concentrating on planning, collaboration, priorities, resource allocation, turnovers, and funding procedures. They posed similar questions for out-of-state agencies (Figure 5), focusing on understanding the factors contributing to successful or unsuccessful TSP implementation. They applied this data to address the challenges and concerns within Illinois.

General Information:

1. What is your current status and vision year for TSP implementation? (e.g., resources, fleet size, etc.)
2. What were your TSP projects, and were they all successful?
3. What are your other transportation projects? Do they have any conflicts or priorities with TSP?

Planning:

4. What is the administrative procedure for starting a TSP project in your corridors? Are they different across the projects?
5. What are your efficiency criteria, and how do you break down the total length of a corridor in some sections? (e.g., based on the performance metrics?)
6. What is your desired outcome? (e.g., reducing delay, travel time, etc.)

Collaboration:

7. Which organizations do you collaborate with on TSP projects?
8. Do you have any common corridors with other transit agencies?
9. What are the inter-agency collaboration challenges for you?

Priorities:

10. What are your priorities for TSP implementation? Are these priorities different from those of other organizations? How do you address these challenges in practice?
11. What are your conflicts with other organizations?

Concerns:

12. Do you have accessibility and permit issues?
13. Are there any other concerns?

Staffing:

14. How many TSP-designated staff do you have?
15. During TSP implementation, did any organization turnover occur?

Figure 2. Questionnaire. List of questions used for interviews with transit agency experts.

As the two main planning centers (Metropolitan Planning Council [MPC] and Center for Neighborhood Technology [CNT]), we want to ask for your opinion and solutions on these issues:

Collaboration

1. The CNT and MPC missions include promoting more equitable and sustainable urban communities. What are your organization's thoughts on TSP, its implementation pace, and the zonal equity it has provided in Chicago so far?
2. Have there been any communications among your organizations, CDOT, IDOT, PACE, and CTA, regarding transit signal priority?
3. Have CNT/MPC implemented any survey to understand the public opinion or any research about the transit system in Chicago and the improvements (such as TSP) needed in this regard?
4. Have CNT/MPC been involved in any stage of the TSP implementation? (e.g., planning, etc.)

Challenges

5. Have CNT/MPC offered any solutions for the challenges in the business procedure of TSP implementation, which is considered a time-scheduling barrier? (e.g., access to infrastructure, obtaining permits, traffic signal system upgrades, etc.)
6. Have CNT/MPC offered any solutions for the challenges in the business procedure of TSP implementation, which is considered a financial barrier? (e.g., staffing, obsolete equipment, etc.)
7. What is the CNT/MPC solution to enhance the TSP implementation procedure and the coordination between multiple agencies? (e.g., Memorandum of Understanding (MOU))

Manuals

8. Transit priority treatments include a wide range of roadway design, operations, and enforcement actions that can help buses and other transit vehicles avoid traffic congestion, reduce signal delays, and move more predictably on all types of roads, and transit signal priority is one of the treatments. However, according to the emailed manuals (PART draft manual, SPUR, and RTA), we want to know your organization's opinion on the other effective parameters in TSP planning.
9. Since delaying is the primary planning criterion for TSP implementation, what factors, in your organization's opinion, contribute to delay and the reduction in bus speeds in both urban and suburban regions? (Lack of infrastructure, congestion, etc.)
10. As pointed out in the PART draft manual, geometric design standards (curb radius at intersection, line-of-sight rules, etc.) affect delay by causing problems for larger vehicles, pedestrians, and other vehicles. What is your organization's solution for changing design standards to speed up TSP implementation?

Figure 3. Questionnaire. List of questions used for interviews with experts from the MPC and CNT.

Collaboration

1. What is your role in TSP deployment and permits?
2. How do you collaborate with other DOT bureaus on TSP implementation?
3. As one of the programming bureau's responsibilities is developing the corridors, what are your criteria for TSP corridor selection in terms of area coverage?
4. What is the current practice and how should the corridors be selected for TSP?
5. What are your criteria for selecting corridors for TSP implementation?
6. Which consultants are you working with and what are their responsibilities?
7. Do you have any projects that conflict with TSP? If so, how do you address them?
8. Are you involved in the controller programming area?

Funding

9. How is the procedure for receiving funds from RTA, CMAQ, and the federal government?
10. Can you submit joint proposals for common corridor projects due to the financial and operational differences?

Figure 4. Questionnaire. List of questions used for interviews with state agency experts.

1. How do you address communication and coordination challenges between your DOTs and transit agencies?
2. Do you use signal timing metrics and vendors?
3. Do you have a centralized system?
4. Do you have a dedicated traffic engineer for TSP?
5. How often are your coordination meetings?
6. Do you have a team of experts or a panel to translate the needs of transit agencies to DOTs?

Figure 5. Questionnaire. List of questions used for interviews with out-of-state agency experts.

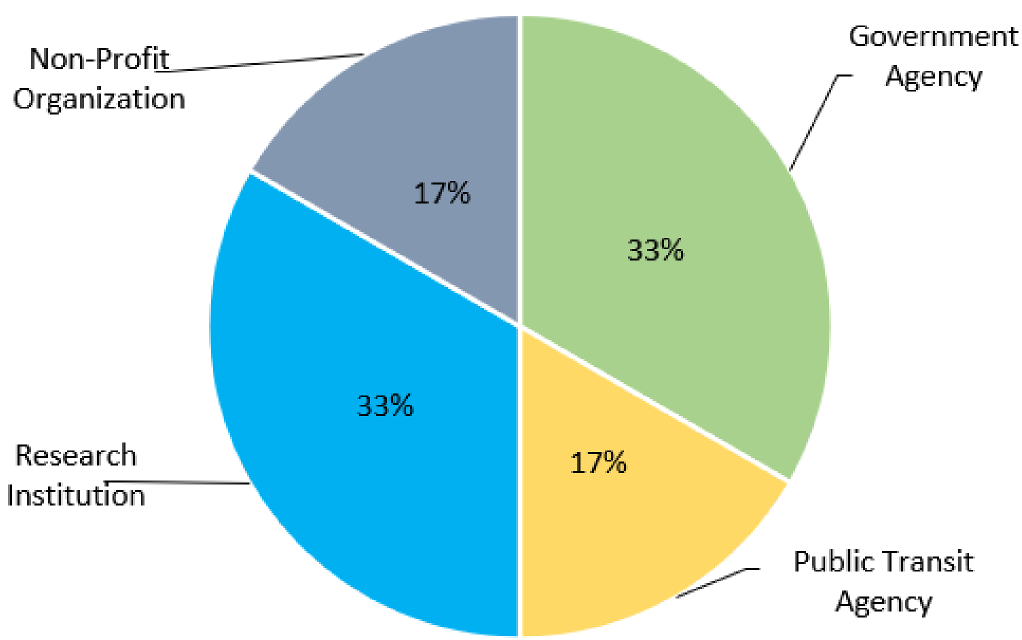
In the second part, based on the key challenges identified during the interviews (as will be discussed in Chapter 4), the research team designed a questionnaire following a multi-criteria decision-making structure to assess the relative importance of the identified barriers affecting TSP program implementation. The research team then distributed the questionnaire link to experts in the Chicago region and asked participants to rank the listed barriers and sub-barriers.

We designed a questionnaire to capture the relative importance of various factors and sub-factors impacting TSP program implementation. Participants were asked to rank the main barriers and sub-barriers using a Saaty 1–9 scale (Saaty, 1989) where a lower number indicates higher priority (Table 2). Experts from various organizations, including public transit agencies, government agencies, research institutions, and consultants, participated in the survey. The survey collected demographic information, such as organization type, field of expertise, and the participant's years of experience.

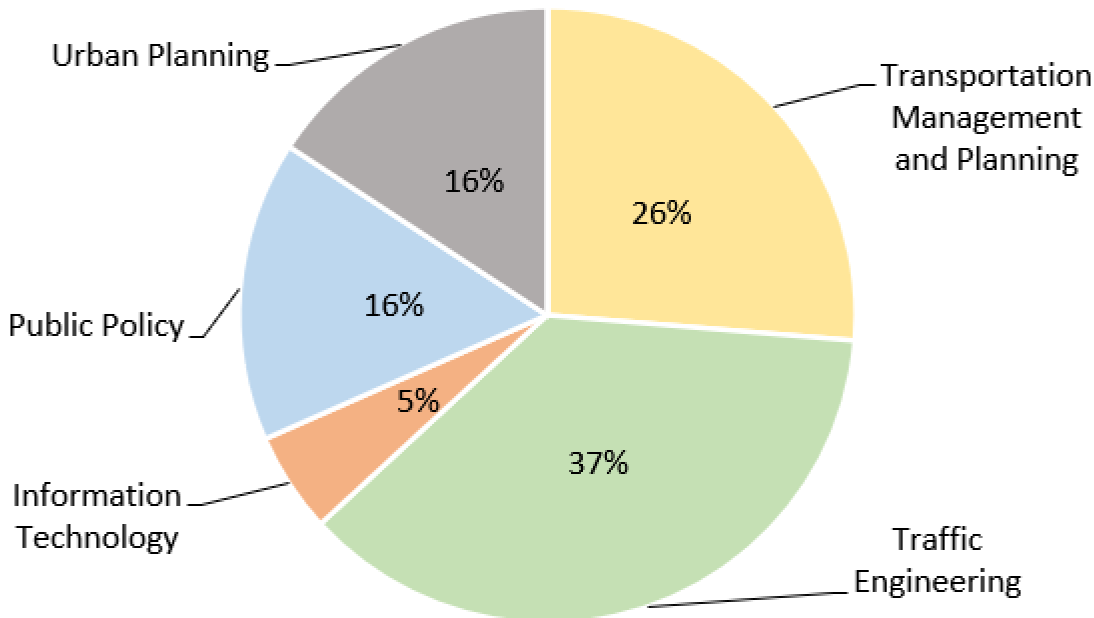
Table 2. Scale of Analytical Hierarchy Process Value from Saaty (1989)

Level of Importance	Definition	Explanation
1	Equally important compared to others	The two criteria contribute equally to the goal
3	Moderately important compared to others	Ratings slightly favor one criterion over another
5	Strongly important compared to others	Rating strongly supports one criterion over another
7	Very strongly important compared to others	Ratings strongly support one criterion over another
9	Extremely important compared to others	Evidence supporting one criterion over another has the highest possible validity
2, 4, 6, 8	Score between two adjacent assessments	When compromise is needed
Opposite	Score for reverse comparison	If criterion i has one of the above numbers compared to criterion j, then j has the opposite value when compared to i.

Figure 6-a shows the distribution of respondents (N = 12) across different groups. Among the respondents, 17% were from public transportation agencies, 33% were from government agencies, 17% were from nonprofit organizations, and 33% were from research institutions. Figure 6-b illustrates the distribution of respondents based on their areas of expertise. Among the respondents, 37% specialized in traffic engineering, 26% in transportation planning and management, 16% in urban planning, 16% in public policy, and 5% in information technology (as shown in Figure 6).



(a) Industry distribution of respondents



(b) Field of expertise distribution

Figure 6. Chart. Distribution of participants in TSP survey by organization type and area of expertise.

METHODS OF ANALYSIS

The research team used thematic analysis to identify the most significant barriers based on a literature review and interview transcripts. Thematic analysis can identify, analyze, and report themes within qualitative data and serves as a bridge between quantitative and qualitative methods (Braun & Clarke, 2022). They also used a topic modeling approach, namely non-negative matrix factorization, to extract the main barriers. In the following sections, they detail the non-negative matrix factorization method.

Paatero and Tapper (1994) introduced non-negative matrix factorization, and Lee and Seung (1999) developed it as an efficient technique for topic modeling, which helps create a better and more structured analysis of textual data (Belford et al., 2018). One advantage of non-negative matrix factorization over traditional methods like latent Dirichlet allocation is that it involves fewer parameters in the modeling process and can identify more homogeneous topics (O'Callaghan et al., 2015). Non-negative matrix factorization is an unsupervised statistical method used for dimensionality reduction of non-negative matrices. It works with term-document matrices and decomposes them into two non-negative factors, *W* and *H*. In the non-negative matrix factorization model, the term-document Matrix A is approximated as the product of two matrices *W* and *H*. Matrix W represents the document membership weights in various topics, while Matrix H represents the term weights in the topics. By sorting the rows of Matrix H, topic descriptors can be obtained, where each row ranks the terms according to their relevance to the corresponding topic.

The process typically begins with the random initialization of non-negative weights in the *W* and *H* factors. Then, using optimization algorithms such as alternating least squares, these factors are iteratively improved to reduce approximation error and reach a local minimum. Two common objective functions used to generate the *W* and *H* factors are the following in Figure 7 and Figure 8 (O'Callaghan et al., 2015):

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\left(V_{\{ij\}} - (WH)_{\{ij\}}\right)^2 = \ || V - WH ||_F^2$$

Figure 7. Equation. Euclidean distance objective functions to generate *W* and *H*.

$$D(V\ ||WH) = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(V_{ij}\ log\frac{V_{ij}}{WH_{ij}}\right)$$

Figure 8. Equation. Kullback-Leibler divergence objective functions to generate *W* and *H*.

The objective functions, such as the Euclidean distance or Kullback-Leibler divergence, are used to measure this discrepancy. Optimization algorithms—including multiplicative update, gradient descent, and alternating least squares, among others—are employed to iteratively update the matrices until convergence to a minimum decomposition error is achieved (Guo et al., 2024).

Finally, the research team used the fuzzy analytical hierarchy process, one of the most commonly used methods in transport studies (Yannis et al., 2020), to determine the relative importance of each main barrier and sub-barrier. This method extends the traditional analytical hierarchy process by incorporating fuzzy logic (Zadeh, 1965) to handle the uncertainty inherent in human judgments. The fuzzy analytical hierarchy process involves several systematic steps that lead to the calculation of local and global weights for the criteria and sub-criteria.

Step 1: Constructing a Hierarchical Framework

The process begins by constructing a hierarchical framework that organizes the problem into a structured hierarchy. This framework consists of the main goal at the top level, followed by main barriers (criteria) and sub-barriers (sub-criteria). By breaking down the problem into a hierarchy, decision-makers (experts) can focus on manageable components to address complex issues more effectively. This organization aligns with the principle that most decision-makers can optimally handle seven to nine elements simultaneously.

Step 2: Forming a Panel of Decision-Makers

The next step is to form a panel of decision-makers, comprising experts with relevant knowledge and experience in the field. These experts are tasked with evaluating and assigning weights to each barrier and sub-barrier. The diverse perspectives that this panel provides are crucial to ensuring that the evaluation considers all relevant factors and insights.

Step 3: Identifying Linguistic Variables and Establishing the Fuzzy Scale

To facilitate systematic comparisons of the importance of each pair of criteria, identify linguistic variables and convert them into triangular fuzzy numbers (Zadeh, 1975). Each linguistic term (Table 3) is associated with a triangular fuzzy scale, which captures the range of possible values that reflect the inherent uncertainty in human judgment. Triangular fuzzy numbers represent each linguistic term, defined by a triplet (l, m, u) where:

- l (lower limit): the minimum possible value
- m (modal value): the most likely value
- u (upper limit): the maximum possible value

Table 3. Linguistic Scales and Fuzzy Scales for Importance

Linguistic scale for importance	Triangular fuzzy conversation scale	Triangular fuzzy reciprocal scale
Equally important	(1, 1, 1)	(1, 1, 1)
Weakly important	(1, 3, 5)	(1/5, 1/3, 1)
Fairly important	(3, 5, 7)	(1/7, 1/5, 1/3)
Strongly important	(5, 7, 9)	(1/9, 1/7, 1/5)
Absolutely important	(7, 9, 11)	(1/11, 1/9, 1/7)

Step 4: Constructing Fuzzy Pairwise Comparison Matrices

Fuzzy pairwise comparison matrices are constructed to capture the relative importance of each pair of criteria. In these matrices, each element $\tilde{a}_{ij}$ is a triangular fuzzy numbers comparison value representing the relative importance of criterion *i* compared to criterion j. This matrix $\tilde{A}$ is defined as follows in Figure 9:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix}$$

Figure 9. Equation. Fuzzy pairwise comparison matrix.

where $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ represents the fuzzy comparison value between criterion *i* and criterion *j*.

Step 5: Calculating Fuzzy Weights

The next step involves calculating each criterion’s fuzzy weights using the pairwise comparison matrix. This calculation is performed through the following steps:

- Geometric Mean Calculation: For each criterion *i*, the geometric mean of the fuzzy comparisons is calculated as shown in Figure 10:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{1/n} \quad \text{for} \quad i = 1,2,\dots,n$$

Figure 10. Equation. Fuzzy geometric-mean calculation.

Here, $\tilde{r}_i$ represents the geometric mean of the fuzzy comparison values for criterion *i*.

- Fuzzy Weight Normalization: Normalize the geometric means to derive the fuzzy weights $\widetilde{w}_i$, as presented in Figure 11:

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n)^{-1} \text{ for } i = 1,\dots,n,$$

Figure 11. Equation. Fuzzy weight calculation.

The fuzzy weights $\widetilde{w}_i$ indicate the relative importance of each criterion in the hierarchy.

- Fuzzy Weight Vector: The resulting vector of fuzzy weights is expressed as follows in Figure 12:

$$\widetilde{W} = [\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n]^{\mathrm{T}}$$

Figure 12. Equation. Fuzzy weight vector.

Step 6: Defuzzification and Consistency Check

To ensure the fuzzy comparisons are meaningful and consistent, the fuzzy numbers are defuzzified into crisp values. This process involves converting the triangular fuzzy numbers comparison value to single numeric values:

- Defuzzification: Convert the fuzzy numbers into crisp values using the method that Lee and Li (1988) proposed, presented in Figure 13:

$$\left(a_{ij}^{\alpha}\right)^{\lambda} = \left[\lambda . l_{ij}^{\alpha} + (1-\lambda) u_{ij}^{\alpha}\right], 0 \le \lambda \le 1, 0 \le \alpha \le 1$$

Figure 13. Equation. Defuzzification.

Where:

$l_{ij}^{\alpha} = \left(m_{ij} - l_{ij}\right) . \alpha + l_{ij}$ is the left-end value of the α-cut for a_{ij}.

$u_{ij}^{\alpha} = u_{ij} - \left(u_{ij} - m_{ij}\right) . \alpha$ is the right-end value of the α-cut for a_{ij}.

α is a value between 0 and 1, representing the decision-making environment's stability.

λ is a parameter between 0 and 1, indicating the decision-maker's optimism (0 for optimistic, 1 for pessimistic).

- Consistency Index (CI): Calculate the consistency index to ensure the comparisons are consistent (Figure 14):

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Figure 14. Equation. Consistency index.

where, $\lambda_{\max}$ is the maximum eigenvalue of the comparison matrix, and *n* is the matrix's dimension.

- Consistency Ratio (CR): Assess the consistency ratio to verify the matrix's consistency:

$$CR = \frac{CI}{RI(n)}$$

Figure 15. Equation. Consistency ratio.

where, $RI(n)$ is a random index that depends on the dimension *n* of the matrix (Table 4).

Table 4. Random Index of Random Matrices

n	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI(n)	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Step 7: Aggregating Group Judgments

In cases where multiple decision-makers are involved, the individual judgments need to be aggregated into a group consensus. This step uses the aggregation of individual judgments (AIJ) method to combine individual assessments into a collective group judgment matrix. The AIJ method aggregates the fuzzy comparisons across all decision-makers (Pereira et al., 2024).

$$l_{ij} = \min_{k=1,2,\ldots,K} \left(l_{ijk} \right)$$

Figure 16. Equation. Lower bounds of fuzzy judgments across all experts.

$$m_{ij} = \sqrt[K]{\prod_{k=1}^{K} m_{ijk}}$$

Figure 17. Equation. Aggregating the modal values of fuzzy judgments using the geometric mean.

$$u_{ij} = \max_{k=1,2,\ldots,K}(u_{ijk})$$

Figure 18. Equation. Aggregating the upper bounds of fuzzy judgments across all experts.

Here, l_{ijk}, m_{ijk}, and u_{ijk} are the fuzzy judgment of experts k (k = 1, 2, … , K). This aggregation results in a consolidated view that reflects the panel's collective evaluation.

Step 8: Determining Local and Global Weights

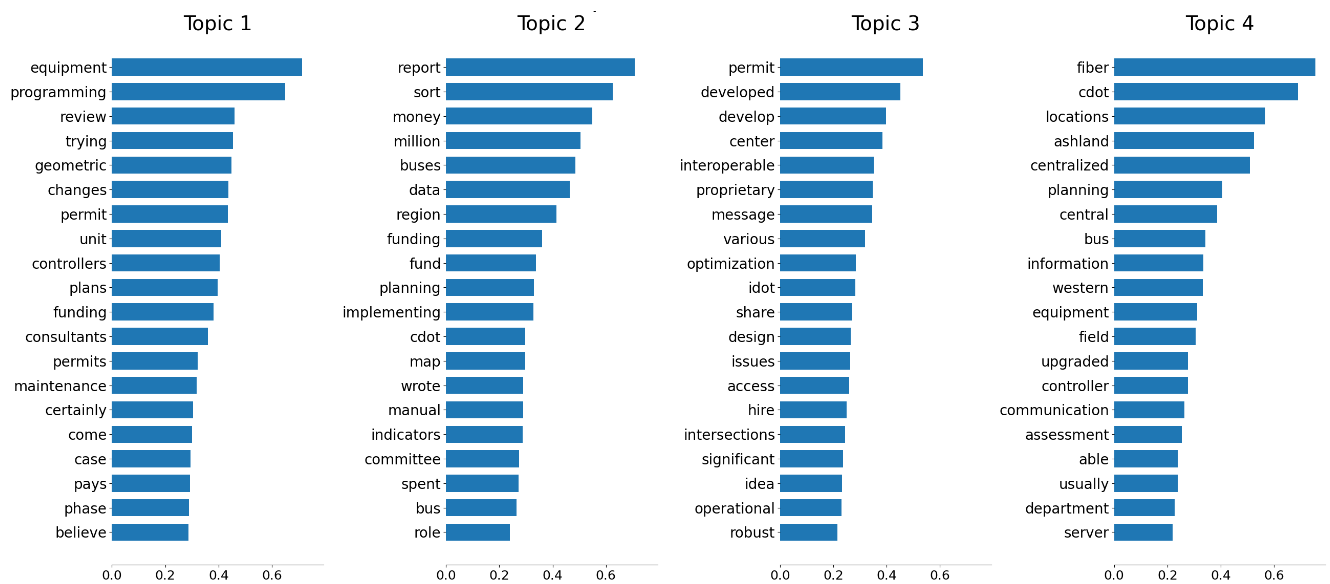
The final step involves respectively calculating both local and global weights for the sub-barriers and main barriers. Local weights are calculated directly from the fuzzy weights for each sub-barrier within a main barrier. They reflect the relative importance of each sub-barrier within its category. Global weights are obtained by multiplying the local weights by the weight of their respective main barriers. This step ensures that the overall prioritization reflects each sub-barrier's contribution to the overall goal.

CHAPTER 4: RESULTS

TOPIC MODELING AND THEMATIC ANALYSIS RESULTS

Figure 19 shows the results of the topics that the non-negative matrix factorization model extracted, with the bar charts displayed above and the corresponding word clouds for each topic shown below.

(a) Word cloud results



(b) Extracted topics from word cloud results

Figure 19. Chart. Results on word clouds (above) and topics extracted by the non-negative matrix factorization model (below).

The thematic analysis of interviews conducted with various stakeholders provided a contextual background that enhances understanding of the factors influencing TSP implementation. Through a detailed thematic analysis of interviews conducted with various DOTs, transit agencies, and traffic controllers, this study identified critical issues across several dimensions.

A predominant challenge is an outdated and heterogeneous infrastructure, which necessitates significant upgrades and regular maintenance. Transitioning from hardware-reliant systems to centralized, cloud-based solutions offers a promising pathway to mitigate these challenges by reducing dependency on physical hardware and enhancing communication efficiency. However, this transition requires substantial financial investment and robust interagency coordination.

Interagency collaboration emerges as a critical factor, with the need for streamlined communication and shared responsibilities among transit authorities, traffic signal operators, and state departments of transportation. Simplifying approval and permitting processes is essential to expedite TSP deployment, which lengthy bureaucratic procedures often delay. Additionally, securing continuous funding through federal, state, and local grants is crucial to supporting initial implementation and ongoing maintenance. Staffing limitations further complicate the implementation process, underscoring the necessity for increased dedicated personnel for TSP projects. Effective project management practices can help mitigate extended implementation timelines, ensuring that TSP systems are deployed in a timely and efficient manner.

Evaluation and impact analysis remain imperative for assessing TSP system performance and effectiveness. However, the lack of data-driven reporting on the efficacy of these systems poses a challenge for budget allocation since decision-makers require clear evidence of TSP benefits to justify financial investment. In this regard, decentralization presents an additional challenge, as fragmented systems hinder comprehensive performance evaluations and complicate funding decisions. Based on the thematic analysis results, we categorized the barriers into four main groups. Table 5 shows the main and sub-factors related to each category.

Table 5. Main Barrier and Sub-Barriers to Implementation of the TSP Program

Main Factor	Sub-Factors
Organizational Factors	Staff Turnover and Labor Shortages
	Legal Issues with Traffic Controller Equipment
	Access to Technical Tools by Transit Providers
	Interagency Operability of the TSP System
Policy and Regulatory Factors	Compatibility of Equipment
	Access and Security Concerns
	Establishing Regional TSP Guidelines
Funding Factors	High Costs of Infrastructure Upgrades
	Dependence on Federal Funding
	Dependence on Local Funding
	Budget Allocation and Prioritization
Technical and Technological Factors	TSP Technology Infrastructure
	Complexity of TSP Systems
	Centralizing Systems
	Integration with Existing Infrastructure
	On-Board Automatic Vehicle Locator Systems

TRANSFORMING DECISION-MAKER EVALUATIONS INTO RELATIVE WEIGHTS

Using the fuzzy analytical hierarchy process, we determined the weight of each main factor and its sub-factors to TSP program implementation. Figure 20 shows the weights related to the main factors. The results provide a hierarchy of the challenges, with organizational factors being the most critical challenges, followed by policy and regulatory, technical and technological, and funding factors. Figure 21 also shows the results regarding the sub-factors' relative importance. As previously explained, each sub-factor has a local weight that indicates this factor's relative importance within the main category. For example, among policy and regulatory factors, equipment compatibility has the highest priority. After multiplying the weights of each main factor by their sub-factors, the research team obtained unnormalized global weights. Then, they normalized the weights. According to Figure 21, the experts considered staff turnover and labor shortages as the highest priority for addressing TSP system implementation issues. If the goal is to specify each section's priorities, then the local weight should be taken into account. However, in general, the global weight indicates the relative importance of all sub-factors. The research team obtained a consistency ratio less than 0.1 for all matrices, indicating a high level of consistency in the pairwise comparisons. This ensures the reliability of the derived priority weights and validates the robustness of the decision-making process in the fuzzy analytical hierarchy process.

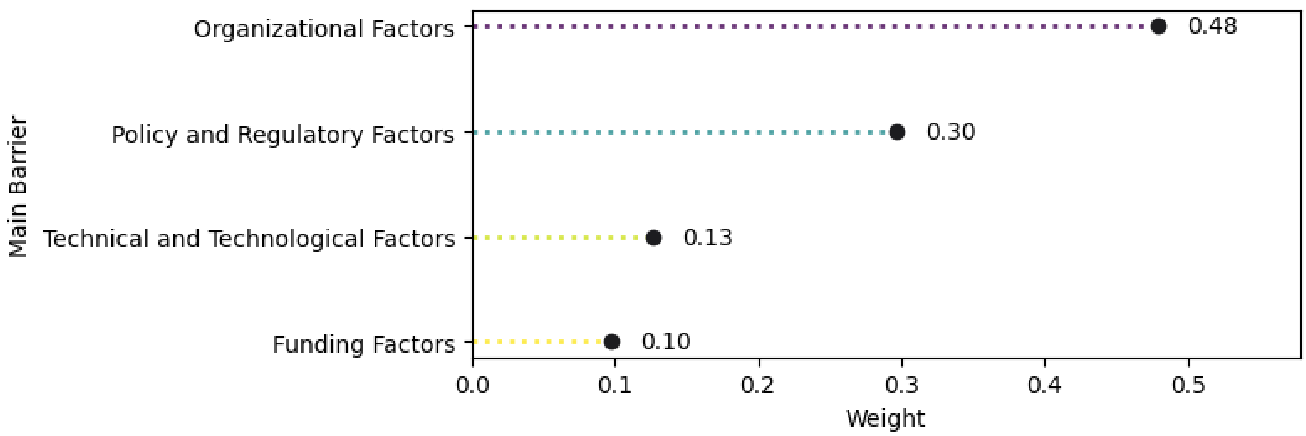


Figure 20. Chart. Prioritization of main barriers in TSP implementation using fuzzy analytical hierarchy process.

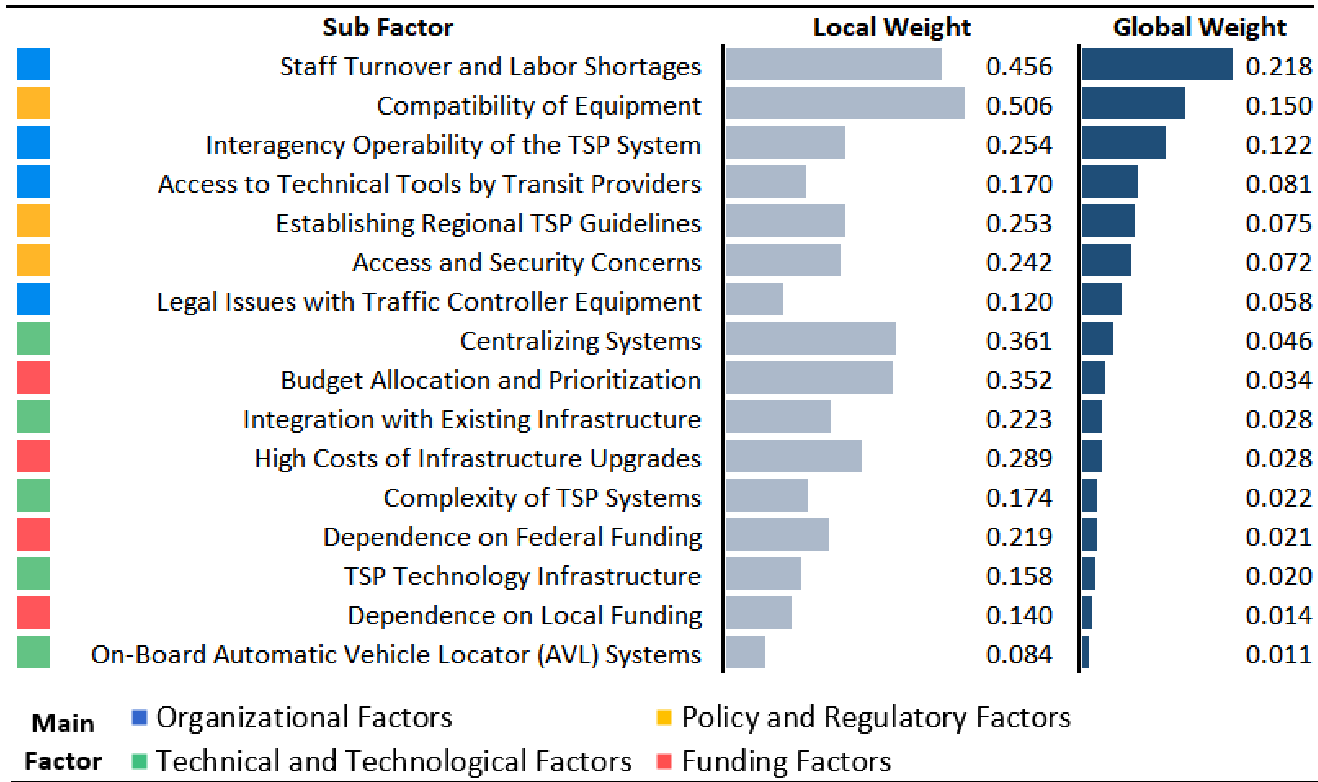


Figure 21. Chart. Relative importance of sub-factors in TSP implementation (local and global weights).

The primary barrier identified is organizational factors, which holds the highest weight in influencing TSP implementation challenges. Within this category, staff turnover and labor shortages emerged as the most significant sub-factor, underscored by a global weight of 0.218. This highlights the impact of inconsistent staffing and inadequate resource management on project continuity and effectiveness. Additionally, interagency operability of the TSP system (global weight 0.121) and access to technical tools by transit providers (global weight 0.081) are notable barriers. These issues highlight the need for strong leadership, seamless cooperation among transit agencies, and sufficient access to necessary technical resources. Agencies frequently mentioned the complexity of collaborating with multiple stakeholders, leading to delays and misaligned objectives.

Policy and regulatory factors also present substantial obstacles, particularly compatibility of equipment (global weight 0.150) and establishing regional TSP guidelines (global weight 0.075). These issues underscore the necessity for streamlined administrative procedures, modernization of traffic signal equipment to support TSP functionality, and development of unified regional guidelines.

Funding constraints were identified as another critical barrier, with budget allocation and prioritization being the most pressing sub-factor (global weight 0.034), followed by high costs of infrastructure upgrades (global weight 0.028). The reliance on federal and local funding, combined with inappropriate budget allocation and prioritization, indicates a need for more strategic financial planning and sustained investment to ensure successful TSP project implementation. The thematic analysis corroborated this finding, revealing that agencies frequently struggle with securing continuous funding. One participant highlighted "replacing the existing system with the centralized system has no grant funding at all," illustrating the ongoing financial challenges transit authorities face.

Technical and technological factors also impede TSP implementation, particularly centralizing systems (global weight 0.048) and integration with existing infrastructure (global weight 0.028). These challenges highlight the complexity of integrating new technologies with legacy systems and the need for cohesive, centralized TSP solutions. Additionally, complexity of TSP systems (global weight 0.022) and TSP technology infrastructure (global weight 0.020) further complicate implementation efforts. The interviews provided further insight into these technical barriers, with several experts pointing out the difficulties in managing diverse and outdated signal infrastructures as well as challenges decentralized systems pose.

Overall, the analysis highlights that organizational factors are the most significant challenges to TSP implementation, followed by policy and regulatory, funding, and technical and technological factors. Addressing these challenges requires a multifaceted approach, including improving organizational stability, streamlining regulatory processes, securing sustainable funding, and modernizing technical infrastructures to support effective TSP deployment.

CHAPTER 5: CONCLUSION

The implementation of transit signal priority (TSP) systems presents a complex array of challenges that must be addressed to enhance urban mobility and transit efficiency. This study highlights the multifaceted challenges to implementing TSP systems in the Chicago region, emphasizing the importance of addressing organizational, policy, funding, and technological challenges. To overcome the challenges to TSP implementation identified in this study, we recommend the following key actions:

Streamlining business processes for permits and engineering reviews. Simplifying these procedures will significantly reduce delays and facilitate quicker TSP system deployment, enhancing overall project efficiency.

Ensuring consistent funding dedicated to TSP implementation at both state and federal levels is crucial. Continuous financial support ensures necessary infrastructure upgrades, equipment acquisition, and system maintenance, enabling long-term TSP operations and transit efficiency improvements.

Establishing a separate entity to oversee permitting and approvals of the TSP system. This entity, comprising representatives from all involved agencies, should have the authority to independently approve and execute plans, eliminating the need for additional approvals from various divisions. A centralized approach would improve coordination and reduce bureaucratic delays. To further enhance efficiency, a centralized system should be adopted for real-time data sharing and decision-making. This system would serve as a unified platform where agencies can monitor, manage, and adjust TSP parameters dynamically based on traffic conditions and schedule adherence.

Expanding resources for transit agencies and DOTs, including staffing and support, to manage overlapping tasks and parallel timelines inherent in TSP projects. The public's growing demand for improved bus services highlights the necessity for adequate resources to ensure smooth and efficient TSP implementation.

Investing in centralized control. A centralized control system and more sophisticated software will improve the development of timing plans and studies, leading to more effective TSP system designs.

Developing a more streamlined process for transitioning from initial data collection and traffic signal system optimization to design and implementation. Expanding central traffic management systems and ensuring consistent coordination between transit agencies and transportation departments will facilitate this approach, reducing project completion times.

An automated TSP management system leveraging AI-driven predictive analytics can significantly reduce bureaucratic inefficiencies by centralizing all signal control, especially in multi-stakeholder areas where coordination among various agencies is complex. By integrating all traffic signals into a unified system, agencies can streamline decision-making while maintaining privacy concerns through secure data-sharing protocols. A centralized platform would allow real-time adjustments to signal timings based on historical and live traffic data, eliminating the need for repeated approvals and manual interventions. Integrating results from different agencies would also ensure a more holistic approach to optimizing transit signal priority while expediting the permit approval process for modifying signals at targeted intersections. This reduces administrative bottlenecks, enhances operational efficiency, and ensures a faster, more adaptive, and responsive transit system without compromising data security and stakeholder collaboration.

REFERENCES

Anderson, P., & Daganzo, C. F. (2020). Effect of transit signal priority on bus service reliability. *Transportation Research Part B: Methodological*, *132*, 2–14. https://doi.org/10.1016/j.trb.2019.01.016

Anderson, P., Walk, M. J., & Simek, C. (2020). *Transit Signal Priority: Current State of the Practice* (No. TCRP 149). Transportation Research Board. https://doi.org/10.17226/25816

Baker, R. J., Dale, J. J., Head, L., Ivanovic, M., Jarzab, J. T., McCormick, D., Obenberger, J., Smith, L., & Stoppenhagen, G. R. (2002). *An overview of Transit Signal Priority (TSP)*. ITS America.

Belford, M., Mac Namee, B., & Greene, D. (2018). Stability of topic modeling via matrix factorization. *Expert Systems with Applications*, *91*, 159–169. https://doi.org/10.1016/j.eswa.2017.08.047

Braun, V., & Clarke, V. (2022). *Thematic analysis: A practical guide*. SAGE.

Guo, Y.-T., Li, Q.-Q., & Liang, C.-S. (2024). The rise of nonnegative matrix factorization: Algorithms and applications. *Information Systems*, *123*, 102379. https://doi.org/10.1016/j.is.2024.102379

Lee, D. D., & Seung, H. S. (1999). Learning the parts of objects by non-negative matrix factorization. *Nature*, *401*(6755), 788–791. https://doi.org/10.1038/44565

Lee, E. S., & Li, R.-J. (1988). Comparison of fuzzy numbers based on the probability measure of fuzzy events. *Computers & Mathematics with Applications*, *15*(10), 887–896. https://doi.org/10.1016/0898-1221(88)90124-1

MBTA. (2024). *Better Bus Project*. Massachusetts Bay Transportation Authority. https://www.mbta .com/projects/better-bus-project

NYC DOT. (2018). *Green Means Go Transit-Signal Priority*. York City Department of Transportation. https://www.nyc.gov/html/brt/downloads/pdf/brt-transit-signal-priority-july2017.pdf

O'Callaghan, D., Greene, D., Carthy, J., & Cunningham, P. (2015). An analysis of the coherence of descriptors in topic modeling. *Expert Systems with Applications*, *42*(13), 5645–5657. https://doi.org/10.1016/j.eswa.2015.02.055

Paatero, P., & Tapper, U. (1994). Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values. *Environmetrics*, *5*(2), 111–126. https://doi.org/10.1002/env.3170050203

Pereira, V., Basilio, M. P., & Santos, C. H. T. S. H. T. (2024). *Enhancing Decision Analysis with a Large Language Model: pyDecision a Comprehensive Library of MCDA Methods in Python* (No. arXiv:2404.06370). arXiv. https://doi.org/10.48550/arXiv.2404.06370

RTA. (2019). *Evaluation report for the regional transit signal priority implementation program (RTSPIP) (Version 2.0). Regional Transportation Authority.* Regional Transportation Authority. https://rtams.org/sites/default/files/digital_documents/Evaluation%20Report%20for%20the%20Regional%20Transit%20Signal%20Priority%20Implementation%20Program%20%28RTSPIP%29.pdf

Saaty, T. L. (1989). Group Decision Making and the AHP. In B. L. Golden, E. A. Wasil, & P. T. Harker (Eds.), *The Analytic Hierarchy Process: Applications and Studies* (pp. 59–67). Springer.

https://doi.org/10.1007/978-3-642-50244-6_4

Shalaby, A., Hu, W. X., Corby, M., Wong, A., & Zhou, D. (2021). Transit signal priority: Research and practice review and future needs. In G. Currie (Ed.), *Handbook of Public Transport Research*. Edward Elgar Publishing. https://doi.org/10.4337/9781788978668.00024

Shalaby, A., Lee, J., Greenough, J., Hung, S., & Bowie, M. D. (2006). Development, evaluation, and selection of advanced transit signal priority concept directions. *Journal of Public Transportation*, *9*(5), 97–120. https://doi.org/10.5038/2375-0901.9.5.6

Smith, H. R., Hemily, B., & Ivanovic, M. (2005). *Transit Signal Priority (TSP): A Planning and Implementation Handbook*. ITS America. https://trid.trb.org/View/772546

Vlachou, K., Collura, J., & Mermelstein, A. (2010). Planning and deploying transit signal priority in small and medium-sized cities: Burlington, Vermont, case study. *Journal of Public Transportation*, *13*(3). https://doi.org/10.5038/2375-0901.13.3.6

Wu, K., & Guler, S. I. (2019). Estimating the impacts of transit signal priority on intersection operations: A moving bottleneck approach. *Transportation Research Part C: Emerging Technologies*, *105*, 346–358. https://doi.org/10.1016/j.trc.2019.06.003

Yannis, G., Kopsacheili, A., Dragomanovits, A., & Petraki, V. (2020). State-of-the-art review on multi-criteria decision-making in the transport sector. *Journal of Traffic and Transportation Engineering (English Edition)*, *7*(4), 413–431. https://doi.org/10.1016/j.jtte.2020.05.005

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning—I. *Information Sciences*, *8*(3), 199–249. https://doi.org/10.1016/0020-0255(75)90036-5

Illinois Department of Transportation

ILLINOIS