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# EXAMINING THE SAFETY IMPACTS OF TRANSIT PRIORITY SIGNAL SYSTEMS USING SIMULATION TECHNIQUES

**Summary.** Transit Priority Signal (TPS) systems are increasingly used to improve traffic efficiency and reduce passenger waiting times. However, such systems may carry potential safety risks. This study aims to investigate the safety effects of TPS at intersections. Our study utilized the SUMO traffic simulation program to create a road network model containing nine signalized intersections. Subsequently, the TPS system was applied to selected bus routes within the road network, and the cases with and without TPS implementation were compared in terms of safety and performance. In safety-oriented comparisons, surrogate safety measures were employed, including number of conflict and Time to Collision (TTC). Signalized intersection performances were measured and compared in terms of the number and duration of stops. The analysis results indicate that TPS enhances safety and transportation performance for buses, but adversely impacts safety and transportation performance for passenger cars. This study underscores the importance of considering safety aspects in the implementation of TPS aimed at improving passenger transportation efficiency. These findings may contribute to the enhancement of public transportation infrastructure and the implementation of appropriate safety measures.

**Keywords:** transit priority signal, traffic safety, SUMO, surrogate safety measures

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## 1. INTRODUCTION

Public transportation plays a vital role in modern urban mobility, providing a sustainable and efficient means of transportation for millions of people. To improve the quality of public transportation services and reduce passenger waiting times, Transit Signal Priority (TSP) systems have been widely adopted. These systems prioritize public transit vehicles at traffic signals and aim to reduce passenger delays. Since buses are the predominant mode of transportation moving on road networks, this system is also referred to as Bus Priority System (BPS).

Numerous studies have reported that TSP technology reduces passenger waiting times and enhances the quality of public transportation services. While the efficiency and potential benefits of TSP have been extensively discussed and researched [1-6], equal attention must be paid to its impact on road safety. Intersections are known to be areas where traffic accidents frequently occur, particularly due to rear-end collisions that can increase with abrupt signal changes. Therefore, it is crucial to comprehensively assess the safety aspects of these systems to ensure the well-being of both public transportation users and other road users. Shahla and others suggest that the use of TSP technology can potentially extend the green light duration when public transit vehicles approach the intersection during their green phase, which may confuse drivers [7]. Furthermore, the researcher found that especially in intersections with long green light durations, pedestrians tend to violate red lights.

Recent studies focusing on the safety implications of TSP have yielded mixed results. In the study by [8], microsimulation was employed to investigate the safety levels of intersections using TSP. Surrogate Safety Measures (SSMs) were used to enable safety assessments by validating the relationship between existing accident statistics and SSMs. The simulations indicated that the TSP system could adversely affect safety performance. Song and Noyce conducted an experimental Bayesian before-and-after analysis using TSP application data in King County, Washington [9]. They examined 11 transit corridors with effective TSP and 75 street segments without TSP. The study claimed a 13% reduction in total accidents, along with a 5% reduction in fatal and injury accidents. It was also mentioned that future studies would include pedestrian and bicycle groups. In a subsequent study, Song and Noyce analyzed accidents before and after TSP implementation in Oregon using a discontinuous time-series method [10]. The analysis revealed a 4.5% reduction in all accidents, but an increase in accidents involving pedestrians and cyclists was noted. The data from Automatic Vehicle Location devices installed on buses were used to conduct a new study [11]. In the study, the bus speed fluctuation metric was used as a SSMs to examine the safety impact of TSP. The results indicated that buses experienced fewer stops and smoother transitions compared to other intersections. While it was suggested that this could reduce bus accidents, no analysis was conducted on its effect on other modes of transportation. In the studies [12,13], potential safety advantages in various regions of Florida equipped with the TSP system were explored. The scientists examined 12 corridors equipped with the TSP system and 29 comparison corridors without it. The analysis results indicated a 7.2% reduction in total accidents, although the detected reduction in rear-end collisions was not statistically significant. Additionally, while various types of accidents were claimed to have decreased, it was concluded that there was no numerical reduction in all accident types.

Literature reviews have shown that while some studies demonstrate positive effects of the TSP system on safety, others argue the opposite. Furthermore, most of these studies emphasize that safety for all modes of transportation is not ensured. Based on these findings, it is evident that research that examines the safety effects of the TSP system from different perspectives could make a significant contribution. This study analyzes the safety effects of the TSP system by considering the entire road network rather than limiting it to a single corridor or signalized intersection. SSMs were used to compare safety levels in the analysis, and these simulations were conducted in a microsimulation environment within a hypothetical road network. Additionally, the waiting times of all buses and other modes of transportation throughout the study area were compared and discussed. This study provides a different perspective from previous research by evaluating the impact of TSP on road safety and analyzing the entire network.

In the following sections, we will first discuss prominent TSP strategies before explaining the simulation setup, hypothetical road network and traffic flow scenarios, and data collection methods used to assess the safety and performance of TSP. The results of these simulations will provide valuable insights into balancing public transportation efficiency and road network safety.

## 2. METHODOLOGY

In this study, a hypothetical road network was first created using the SUMO traffic simulation program [14] to examine the effects of the TSP approach on safety and performance. Subsequently, traffic flow scenarios determined using the Latin hypercube method were tested on two different road networks, one utilizing TSP technology and the other not. The results include Time to Collision (TTC) and collision count values to determine the safety level, while average waiting times and stopping counts metrics were used to evaluate the intersection performance of TSP. Fig. 1 illustrates the overall structure of the study.

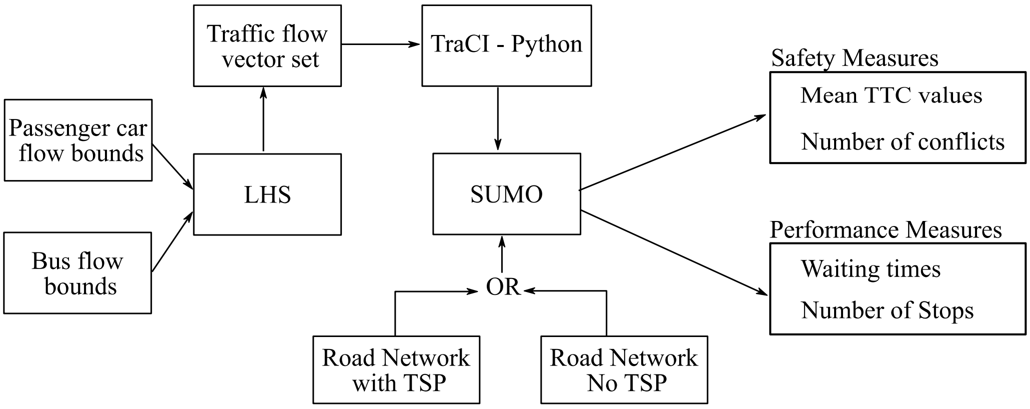

Fig. 1. Overview of procedures

The analysis began with the calculation of traffic flow scenarios using the Latin Hypercube Sampling (LHS) method, as shown in Fig. 1. Then, two road networks, one equipped with the TSP system and the other without, were created in the SUMO environment, including certain intersections. Each traffic flow scenario was simulated for these two road networks using TraCI and Python. At the end of the simulations, safety and performance metric values for buses and Passenger Cars (PC) were collected and analyzed. TraCI is an extension that allows access to and control of systems within the simulation at each simulation step, using Python with SUMO.

### 2.1. Transit priority signal system (TSP)

Transit Priority Signal System (TSP) refers to various methods employed at intersections controlled by traffic signals to enhance public transportation service and reduce delays. It can be divided into two main categories: active and passive priority systems [15]. In the active system, the presence of buses is detected by sensors, while in the passive system, it is assumed that buses approach the intersection according to a certain statistical distribution [16]. Under the categories of active and passive systems, there are specific TSP strategies, which generally work on principles such as extending the signal on the bus approach arm and prematurely terminating the green signal on other conflicting arms or making phase changes.

In this study, in our hypothetical network, the TSP red truncation technique was applied at intersections indicated by red dots in Fig. 2, in conjunction with an Actuated Signal Control System (ASC). In red truncation, when the presence of a bus is detected, the red signal on the arm on which the public transportation vehicle is approaching is prematurely terminated, and it returns to the green signal. To make the system work, area detectors along the route were used at intersections where two bus routes pass, which are located on the central horizontal and vertical axis of the road network, for the purpose of TSP system detecting buses.

### 2.2. Surrogate safety and performance measures

The safety analysis of road segments can be approached in various ways in today's context. Traditional methods involve examining data from past accidents to evaluate the collision risk in an area. On the other hand, collisions are relatively rare events within the flow of traffic interactions [17]. Therefore, it may take years to assess an area from a collision perspective using traditional methods. In contrast to traditional methods, SSMs can be employed to assess safety. SSMs are based on the concept that accidents result from conflicts, which are situations where the probability of a collision is high. These models serve as proactive indicators that provide advance information about the safety of a facility. An essential term frequently used in these proactive studies is *'conflicts*.' A conflict is defined as an observable situation in which two or more road users come together in time and space, posing a risk of collision if their movements remain unchanged.

In this study, commonly used concepts from the literature, Time to Collision (TTC), and the Number of Conflicts (NoC), were utilized SSMs [18–21]. TTC is defined as the remaining time until a potential collision if interacting road users do not change their speed and direction. For two vehicles, TTC is calculated by dividing the distance ($D$) between them at a specific moment by the relative velocity ($\Delta V$) of the two vehicles using Eq 1, as introduced by Hayward [22].

$$TTC = \frac{D}{||\Delta V||} \tag{1}$$

## 3. SIMULATION SETUP

The use of simulation in traffic engineering is quite common, especially due to its cost-effectiveness and the ability to facilitate experiments of various applications before real-world implementation. Additionally, microsimulation technique enables the modeling of complex vehicle interactions, allowing for the presentation of comprehensive results. In this study, the microsimulation program SUMO was employed to investigate the safety implications of TPS.

SUMO was chosen for its reputation for providing reliable microsimulation capabilities and its compatibility with in-depth analysis supported by Python.

The purpose of the simulations conducted in this study was to evaluate whether the implementation of a TPS in a road network raises safety concerns. Therefore, we aimed to assess the impact of such systems on traffic flow from a safety perspective, considering the increasing adoption of intelligent transportation systems in recent years. It is expected that the results of this research will provide valuable insights for traffic engineers on how much these systems should influence their design

### 3.1. Hypothetical road network and traffic flow scenarios

To conduct simulations, a hypothetical road network consisting of nine intersections was created (Fig. 2). The connections within this network consisted of two lanes, and the maximum allowable speed on these lanes was set at 82 kilometers per hour. The distance between intersections was designed to be 500 meters. This type of road network was selected due to its relatively simple configuration, commonly found in large cities.

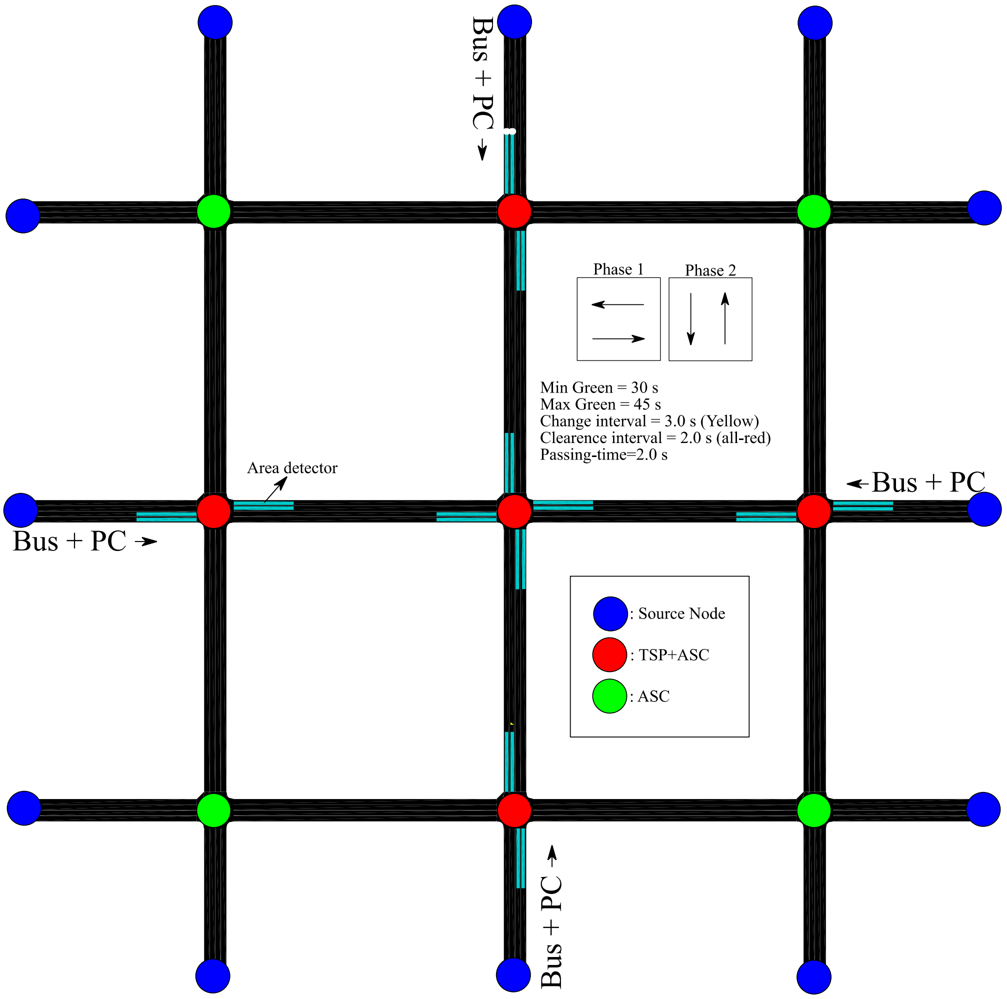

Fig. 2. Representation of hypothetical road network and other systems

It was assumed that two types of transportation were used within the road network: buses and passenger cars (PC). Additionally, it was assumed that bus routes progressed centrally on the road network. Car routes were configured to follow a linear path starting from source nodes, and a no-turn rule was assumed at intersections. Furthermore, pedestrian traffic within the road network was neglected. This simplification aimed to reduce simulation parameters, the required number of simulations, and overall complexity. In Fig. 2, source nodes are highlighted in blue, indicating entry points where both buses and passenger cars had access to the road network. Other source nodes exclusively served as entry points for PCs.

To monitor and record the number of buses within the approach lanes, strategically placed area detectors capable of detecting up to 100 meters behind the Stop line at intersections were installed, as shown in Fig. 2 in turquoise. In the SUMO simulation program, these detectors are referred to as lane area detectors. Additionally, inductive loop detectors placed beneath the road surface were used for the ASC system. The positions of these inductive loop detectors were automatically determined based on the cycle times used in the active signal control system employed by SUMO. Information about the parameters used in ASC (min-max green time, passing time, etc.) and the phase plan is presented in Fig. 2.

### 3.2. Latin hypercube and traffic flow scenarios

As explained in the simulation setup section, there are a total of 12 source nodes in the hypothetical road network, and it is assumed that passenger car (PC) traffic originates from all of these nodes. Additionally, it is assumed that there are bus routes along the roads crossing horizontally and vertically through the network, and bus traffic originates from the source nodes along these routes. As a result, a total of 16 traffic flow variables are created, and these 16 flow variables, taking different values, constitute a single traffic scenario.

In this study, the existence of 16 traffic flow variables necessitates considering a large number of traffic scenarios. Therefore, the Latin Hypercube Sampling (LHS) method, recommended by McKay et al. (1979), aims to reduce the required number of experiments by creating a set of high-quality samples that have a distribution similar to the initial distribution. Consequently, the set of traffic flow scenarios was generated using the LHS method.

For each traffic scenario, a simulation of 3600 seconds was conducted. After the simulations, total conflict counts within each scenario and the Time-to-Collision (TTC) durations for each conflict were recorded for use in safety comparisons, and the average TTC was calculated. As performance metrics, the total stop counts and stop durations for buses and PC were extracted from the simulation results, and the averages of stop durations were calculated. Furthermore, the random-coordinate descent (RCD) optimization method was selected for the LHS process, resulting in the creation of a total of 500 traffic flow scenarios for simulation.

## 4. ANALYSIS RESULTS

In this section, the results obtained from the simulations are presented and discussed with graphs. Different signal control systems were used, and Figure 3 presents graphs showing how the safety level changes, while Figure 4 presents figures showing how the performance of the road network is affected.

When examining the central tendencies for safety elements in Fig. 3, it is evident that the NoC is higher for both PC and buses when the bus priority system (TSP) is used compared to when ASC is used. This observation indicates that TSP may lead to more frequent sudden stops, especially for PC, which could increase the risk of traffic accidents.

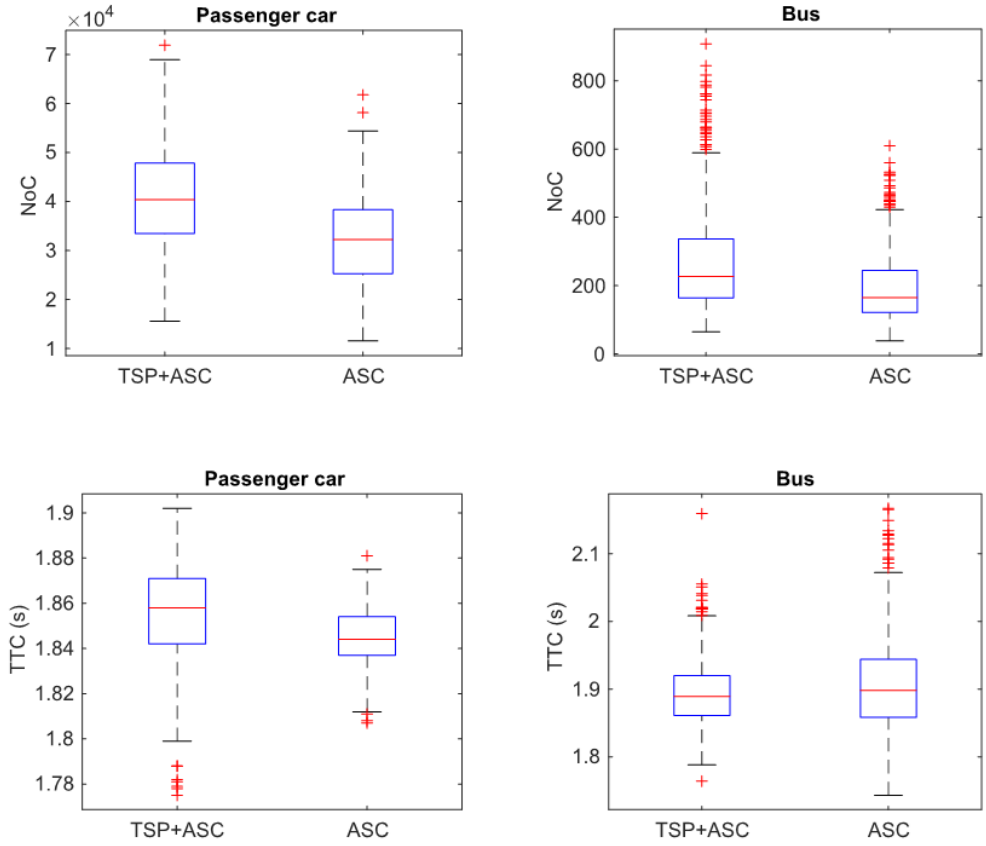

Fig. 3. SSMs with TSP+ASC and ASC systems under different traffic flow scenarios

For TSP usage, it can be observed that some passenger car flow vectors have more conflicts when only ASC is used. This can be observed particularly when considering that the upper bound of the TSP box is approximately 70,000, while the upper bound of ASC is approximately 55,000. A similar situation is observed when examining the bus graph, especially where lower quartile values are higher. This could be because buses are relatively fewer compared to PC. When examining the TTC figures, it is seen that the lower bound for TSP usage is below the first quartile value determined for ASC usage for PC. However, some outliers are observed below the first quartile. ASC usage results in a narrower distribution of TTC values, generally between 1.82 and 1.87 seconds. On the other hand, TSP usage shows that TTC values are spread over a wider range, between 1.8 and 1.9 seconds. In other words, while the median value for TSP usage is slightly higher than ASC, the lower and upper limits are more dispersed, indicating a higher probability of more severe conflict situations in some scenarios. Similarly, when examining TTC distributions for buses, it is observed that TSP usage has a less pronounced distribution compared to ASC usage. With ASC, TTC values range from 1.7 to 1.7 seconds, while with TSP, they range from 2 to 1.8 seconds. In other words, TSP usage reduces the probability of buses experiencing more serious conflicts while potentially increasing the likelihood of PC encountering more serious conflicts. This result is consistent with the expected outcome of TSP, which reduces stopping and braking for bus flows.

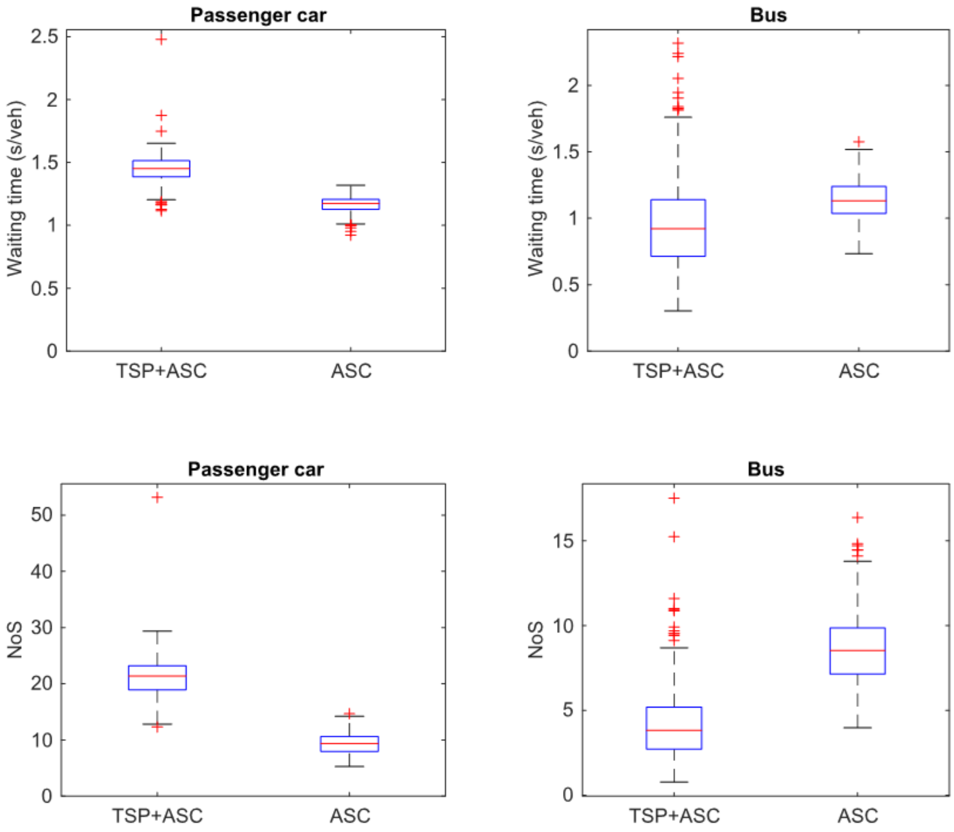

Fig. 4. Performance measures with TSP+ASC and ASC

The changes in road network performance due to TSP usage are shown in Figure 4. The figure separately presents waiting and stopping counts per vehicle for PC and buses. When comparing waiting times for PC, it is clear that TSP usage increases waiting times compared to ASC usage. This is especially evident when looking at median values. Waiting times for PC range from 1.3 to 1.7 seconds with TSP usage, while they range from 1 to 1.3 seconds with ASC usage. Waiting times for buses, on the other hand, are lower on average with TSP usage, as expected. The average waiting time with TSP is just below 1 second, while with ASC, it exceeds 1.2 seconds. Additionally, when looking at the lower quartile boundary, it is clearly seen that 25% of the scenarios require waiting times between 0.3 and 0.7 seconds with TSP usage. On the other hand, in some traffic flow scenarios where buses are located at distances where detectors cannot see them within heavy traffic, waiting times may be higher with TSP usage. As for the average stopping counts, it is observed that PC make more involuntary stops. With TSP usage, PC make an average of approximately 21 stops, while with only ASC, they make approximately 10 stops. However, the situation is reversed for buses. With TSP usage, buses make an average of about 3 stops, while with only ASC, they make an average of about 9 stops. When looking at the lower and upper quartile boundaries, in 75% of the cases, buses make fewer than 5 stops with TSP usage. On the other hand, with ASC usage, 75% of the cases require 7 or more stops. In conclusion, TSP usage significantly increases average waiting times and stopping counts for PC. In contrast, it significantly reduces waiting times and stopping counts for buses.

To summarize, while TSP enhances bus transportation efficiency by reducing waiting times and stopping counts, it does raise potential safety concerns, particularly for passenger vehicles.

Decision-makers and transportation authorities should consider the balance between improving bus performance and potentially increasing safety risks, especially for PC when contemplating the implementation of TSP systems. It is evident that more research and analysis are needed to develop strategies to mitigate safety concerns associated with TSP and to ensure the safe integration of these systems into urban transportation networks.

## 4. CONCLUSION

This study aimed to investigate the effects of Transit Signal Priority (TSP) systems on traffic safety and efficiency for buses and PC. TSP is a system that allows public transportation vehicles to receive priority at traffic signals, potentially enhancing the efficiency of urban transportation. However, it should be noted that these systems may also raise potential safety concerns.

Our analyses were conducted using microsimulation methods, comparing the impacts of TSP strategies' implementation and non-implementation on safety and performance within a road network. The results obtained indicate that TSP systems can enhance the transportation efficiency of buses. It was observed that waiting times and the number of stops for buses decreased, allowing buses to travel more quickly. This could contribute to public transportation vehicles providing services in a timelier and reliable manner.

However, this study also demonstrated that TSP systems may raise safety concerns, particularly by increasing waiting times and the number of stops for PC, potentially increasing the risk of traffic accidents. These concerns reflect the fact that TSP systems may adversely affect traffic safety for PC.

In conclusion, this study provides valuable guidance for decision-makers and transportation authorities regarding the implementation of TSP systems. While these systems have the potential to enhance bus transportation efficiency, they may also raise safety concerns. Therefore, a careful balance is required in the implementation and design of TSP systems. Furthermore, further research is needed to develop strategies to mitigate safety concerns and integrate these systems into urban transportation networks safely.

Future studies should focus on exploring how different TSP strategies impact safety under various traffic conditions and how safety measures can be improved. Additionally, within this context, there should be a more detailed examination of the interaction between public transportation vehicles and private cars.

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