SUMO User Conference 2026
TIBconferencesession
TIB-OP_will_set_DOI
© Authors. This work is licensed under a Creative Commons Attribution 4.0 International License
Published: 1970-01-01

PRE-PRINT VERSION

C-ITS services for light rail systems

Evaluation of TSP and GLOSA for light rail systems in SUMO

Paula von der Heide [1], and Prof. Dr.-Ing. habil. Lars Schnieder [1]

[1] Institute for Railway Engineering and Traffic Safety, Technical University of Braunschweig
*Correspondence: paula.von-der-heide@tu-braunschweig.de

Abstract. In metropolitan areas, light rail systems often operate on underground tracks within city centers, enabling short headways and high operational reliability. Outside the center area, trains transition to the surface. Even if tracks remain largely separated from other traffic, trains experience delays at intersections due to traffic signal phases and surrounding vehicle congestion.

Traffic Signal Priority (TSP) and Green Light Optimal Speed Advisory (GLOSA) are Cooperative Intelligent Transport Systems (C-ITS) services designed to enhance public transport performance at these intersections through real-time vehicle-to-infrastructure (V2I) communication.

This paper presents a microscopic simulation study using SUMO. The scenario models the intersection of Nationalbibliothek in Frankfurt with light rail line U5. Three different scenarios are implemented: a baseline without any public transport priority, a legacy priority scenario reflecting common urban practice today, and a C-ITS scenario combining TSP and GLOSA.

Keywords: Light rail systems, C-ITS, traffic signal priority

1. Introduction

Cities aim to reduce congestion, emissions, and energy consumption. Public transport with high capacity and zero local emissions plays a key role in achieving these objectives. However, reliable and efficient operation is a prerequisite for sustaining user acceptance and encouraging a modal shift towards public transport.

Intersections are the bottlenecks of urban mobility. To enhance the public transport, prioritization at signalized intersections has been implemented for several decades. Since the 1980s, various passive or active priority strategies have been applied to reduce signal-related delays for trains and buses. They are typically based on a predefined registration chain and have limited real-time information.
Recent developments in Cooperative Intelligent Transport Systems (C-ITS) enable a further evolution with services such as Traffic Signal Priority, (TSP) and Green Light Optimal Speed advisory (GLOSA).

This study aims to quantify the performance potential of combined TSP and GLOSA strategies for urban light rail operations at signalized intersections. Using a microscopic simulation, we assess the operational effects on trains while explicitly considering impacts on other traffic participants. C-ITS services have been widely studied for bus operations as for example by Schmidt et al. [1] or Seredynski et al. [2], but their combined effects on light rail systems remain insufficiently quantified. Moreover, the distinct driving dynamics and operational constraints of rail-based vehicles must be considered.

1.1 State of the Art

1.1.1 Urban Railway Systems

In underground tunnel sections, urban rail systems operate largely independent of external disturbances, resulting in comparatively stable and predictable travel times. This stability provides favorable conditions for higher grades of automation. Automated train operation (ATO) systems can follow predefined and energy-efficient speed profiles with high precision. In addition, advanced train control and signaling systems allow for reduced headways by ensuring safe train separation through continuous monitoring and control. Shorter headways directly increase line capacity and improve overall system performance, further enhancing the efficiency of underground rail operations.

In contrast, outer branches of urban rail networks usually operate on surface level. Therefore, rail operations are influenced by traffic signal control, interactions with other road users, and congestion. Even when tracks are largely segregated, intersections remain critical points where movement is governed by signal phases. As a result, trains are influenced by surrounding traffic conditions and experience signal-related delays. Travel times become more variable, and vehicles are often forced into repeated deceleration and acceleration cycles. This stop-and-go operation reduces punctuality and can negatively affect energy efficiency and passenger comfort.

1.1.2 Legacy Priorization of public transport

To mitigate signal-related delays at intersections, public transport prioritization has been implemented in many cities since the 1980s. These conventional systems aim to reduce stopping probability and signal introduced delay for trains and buses by adapting signal control in favor of approaching public transport vehicles. Typical measures include green time extensions, red truncation, phase insertions or skipping [3].

In all active prioritization implementations, the public vehicle first must be detected. This is done by local detection technologies such as inductive loops, infrared transmitters, or radio-based systems positioned at fixed points upstream of the intersection. They build a registration point chain comprising of an advance detection (optional), a primary detection, a door status detection after completing dwell time at a nearby station (optional), and a deregistration detection after the vehicle clears the intersection, see Figure 1. They trigger the public transport vehicle to announce their arrival to the traffic light controller in R.0916 telegrams via analogue radio transmission. [3]

The corresponding green phase is typically granted at a pre-calculated time based on a predefined approach speed and travel time between the registration point and the stop line. This estimation originally relies on a statistical method by Brenner [4]. It is based on static assumptions with no update over time. For Germany, further guidance on implementation and design considerations are provided by the FSGV in an appendix to the RiLSA [5].

PRE-PRINT VERSION

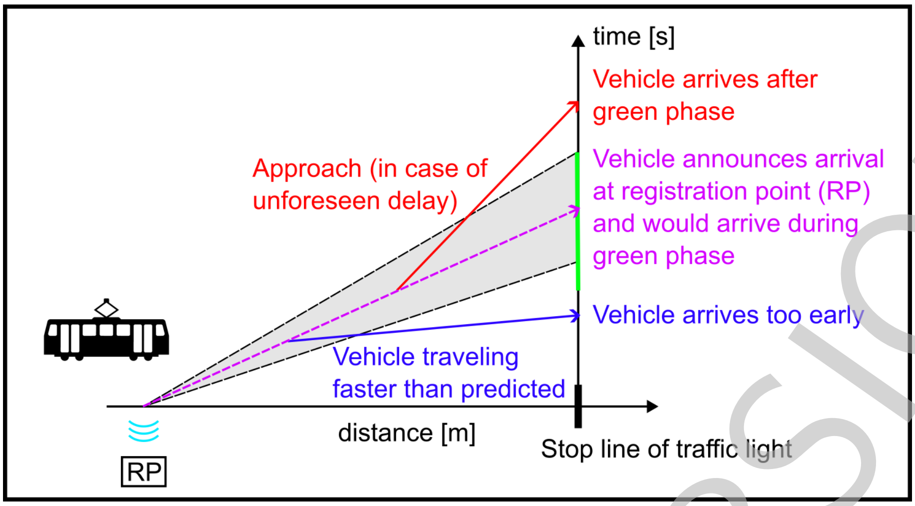


Figure 1. *Prioritization of public transport with registration point chain [6]*

If the vehicle deviates from the expected speed profile due to unforeseen disturbances, it may arrive earlier or later than predicted and consequently miss its allocated green window. In such cases, the green phase may be extended up to its maximum permissible duration, increasing the impact on competing traffic streams. After that, no prioritization can be granted. [6]

1.1.3 Cooperative Intelligent Transport Systems (C-ITS)

C-ITS extends conventional traffic management by enabling direct communication between vehicles and infrastructure (V2I). It is based a on bi-directional data exchange via standardized communication protocols (Open Communication Interface, OCIT).
Over the past decade, several large-scale initiatives have supported the development and standardization of C-ITS in Europe. Projects such as the C-ITS European Corridor, SCOOP@F, and C-Roads have conducted several real-world pilot deployments to support the development of C-ITS services and to advance harmonized implementation across Member States. While many projects initially focused on private vehicle use cases like In-Vehicle Information and RoadWorks warnings, public transport services including Traffic Signal Priority (TSP) and Green Light Optimal Speed Advisory (GLOSA) are now increasingly addressed, for example in KoMoD (Düsseldorf), SIRENE (Braunschweig, Madgdeburg) and BiDiMoVe (Hamburg). An detailed overview is provided in [3].

C-ITS services can also improve operation of light rail systems when interacting with road traffic [7]. The bi-directional communication allows for more dynamic and flexible priority control strategies at intersections. Priority actions are then based on precise and updated trajectory forecasts rather than assumed arrival times. In addition, GLOSA supports vehicles in adapting their approach speed to upcoming signal phases, potentially avoiding complete stops and reducing stop-and-go patterns as well as energy consumption. Compared to legacy systems, C-ITS therefore enables higher temporal accuracy and improved coordination, which aims to reduce the time loss at intersections but also to reduce the impact of priority actions on competing traffic.

With the discontinued frequency allocation for analogue radio transmission in urban transport, many German cities are looking into replacing their public transport prioritization via R09 telegrams with C-ITS which is based on WLAN 802.11p (ITS-G5), see

PREPRINT VERSION

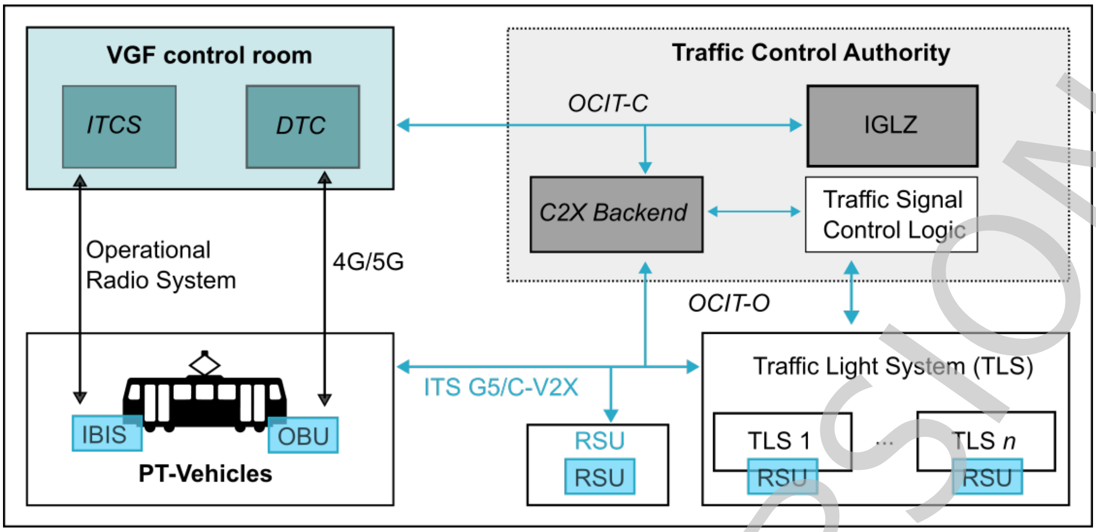


Figure 2. *C-ITS architecture based on [3] and [9]*

VDV 4022 [8]. The public transport operator VGF in Frankfurt is already implementing C-ITS services for their light rail system [9].

To implement this, public transport vehicles have to be equipped not only with an IBIS onboard unit for access to the VGF operations management system (ITCS), but also with an additional Onboard Unit (OBU) for C-ITS. In approach to the intersection, the vehicles will then repetitively transmit a Cooperative Awareness Message (CAM, ETSI EN 302 637-2) with real-time information on position, speed, and estimated time of arrival. The Traffic Light System (TLS) has a Road Side Unit (RSU) which continuously transmits information on Signal Phase and Timing (SPaT, TS 103 301). Phase timing adjustments are governed by the Integrated Control System (in Frankfurt IGLZ). The C-ITS architecture is depicted in Figure 2.

2. Methodical Approach for Simulating C-ITS for light rail systems

This study evaluates the operational benefits of the C-ITS services TSP and GLOSA when applied to urban light rail systems. To this end, a representative signalized intersection in Frankfurt is modeled within a microscopic simulation environment using SUMO. Three scenarios are systematically compared: a baseline without any public transport prioritization, a conventional legacy prioritization approach, and an enhanced C-ITS configuration combining TSP and GLOSA.

2.1 Creation of SUMO scenario

The modeled scenario represents the signalized intersection at Nationalbibliothek in Frankfurt. This location was selected because it constitutes a highly loaded and operationally critical node within the network, where considerable time loss occurs in real-world operation for both public transport and individual traffic. The intersection accommodates complex multi-modal traffic flows with competing signal demands. Owing to these characteristics, the site provides a suitable test case for evaluating different traffic signal prioritization strategies. Moreover, the city of Frankfurt plans to implement C-ITS services at this intersection, which further underlines its practical relevance for the present study.

PRE-PRINT VERSION

2.1.1 Topology

The intersection is a four-arm signalized junction, as shown in Figure 3. Along the North–South axis, the centrally aligned double-track light rail corridor (line U5) runs parallel to motorized traffic in both directions. The East–West axis (interstate B8) accommodates general traffic and bus services (line M32). Additionally, we have a pronounced left-turn movement from the Northern approach. There is a bus station on both directions just behind the intersection. The train station "Nationalbibliothek" is located just South of the intersection. The next train station "Hauptfriedhof" is 500 m North of the intersection but also included in the SUMO scenario, so that we model one stop to stop relation for buses and trains.

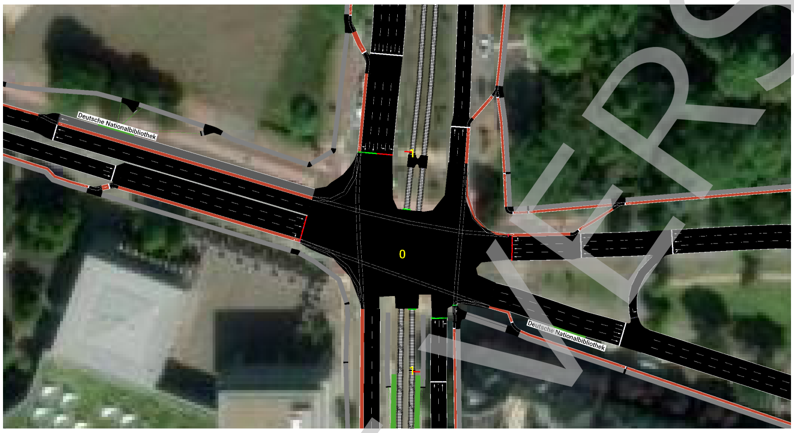


Figure 3. *Signalized intersection at Nationalbibliothek in Frankfurt, as modeled in SUMO.*

2.1.2 Traffic

The simulated traffic consists of light rail vehicles, buses, passenger cars and bicycles. Car and bicycle traffic are generated with random departure times, at fringe origins and destinations. To assess the significance of traffic volumes, three distinct demand levels are implemented, each represented by a corresponding traffic factor.

Table 1. *Number of vehicles generated within the 3-hour simulation period*

	tf = 0.5	**tf = 1.0**	**tf = 2.0**
Trains	72	72	72
Busses	36	36	36
Cars	2 479	4 957	9 914
Bicycles	1 469	2 937	5 873

Light rail operation is based on Frankfurt's line U5. Trains operate every five minutes according to the current timetable (2026). The scheduled running time between the two adjacent stops is approximately two minutes, departure times are set according to the timetable with a minimum dwell time of 20 s. Train separation follows a fixed-block principle with a signaling system, therefore trains use the SUMO car-following model *Rail* which allows only one train present in one section of the track. Moreover, the driving dynamics of light rail vehicles is distinct from cars. We model our own vehicle which resembles key characteristics of the VGF vehicles in Frankfurt, see [10] and [11]. The most significant difference compared to the driving dynamics of cars emerges from different acceleration (max 1.3 m/s compared to 2.6 m/s) and deceleration for service braking (1.0 m/s compared to 4.5 m/s) behavior.

PRE-PRINT VERSION

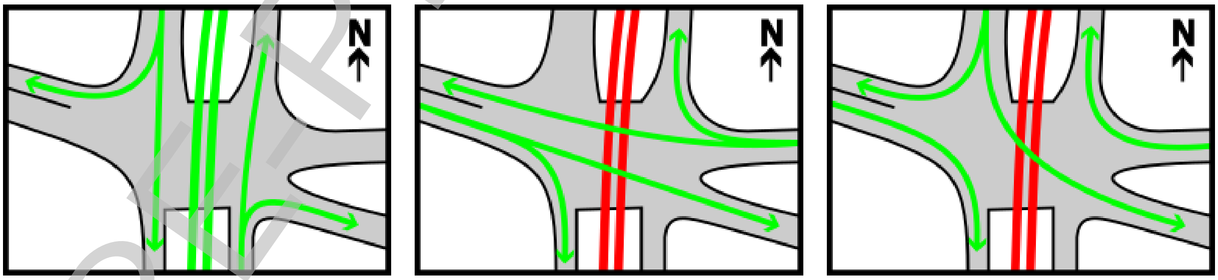
Bus operations along the East–West corridor are modeled according to bus line M32. Buses operate at a ten minute headway based on the current timetable (2026). Running times between stops are implemented according to schedule.

2.1.3 Traffic Light

The intersection is controlled by an actuated SUMO traffic light program consisting of three main green phases: North–South movements (including trains), East–West movements (including busses), and a protected turning phase for the dominant turning demand (notably the strong left-turn from the North). The controller operates with minimum and maximum green constraints (e.g., *minDur=5 s*,*maxDur=50 s*) to ensure responsiveness under fluctuating demand while preventing excessive green times. Each main green phase is followed by a yellow clearance and an all-red phase. Standard yellow intervals are used for road traffic. In addition, an extended yellow interval is inserted for train movements (phase 2) to reflect the longer braking distance and more constrained deceleration behavior of rail vehicles.

```
<tlLogic id="0" type="actuated" programID="0" offset="0">
    <phase duration="20" state="gGggGGrrGrrrrrrrgGgGGGrrrrrrr" minDur="5"
    maxDur="40"/>
    <phase duration="10" state="gGggGGrryrrrrrrrgGgGGyrrrrrrr"/>
    <phase duration="6"  state="yyyyyyrryrrrrrrryyyyyyrrrrrrr"/>
    <phase duration="1"  state="rrrrrrrrrrrrrrrrrrrrrrrrrrrrr"/>
    <phase duration="30" state="rrrrrrrrrGGggGGGrrrrrrGGGggGG" minDur="5"
    maxDur="50"/>
    <phase duration="6"  state="rrrrrrrrryyyyyyyrrrrrryyyyyyy"/>
    <phase duration="1"  state="rrrrrrrrrrrrrrrrrrrrrrrrrrrrr"/>
    <phase duration="10" state="GrrGrrGGrGrrGrrrrrrrrrGrrrGrr" minDur="5"
    maxDur="50"/>
    <phase duration="6"  state="yrryrryyryrryrrrrrrrrryrrryrr"/>
    <phase duration="1"  state="rrrrrrrrrrrrrrrrrrrrrrrrrrrrr"/>
</tlLogic>
```

The three main green phases are illustrated in Figure 4. The target green for prioritization of the light rail traffic is phase 0.



(a) *Phase 0* **(b)** *Phase 4* **(c)** *Phase 7*

Figure 4. *Three main green traffic light phases*

2.2 Comparison of public transport priority mechanisms

We implement three traffic control scenarios: a baseline scenario without public transport priority, a priority scenario representing legacy systems commonly deployed in

PRE-PRINT VERSION

urban networks today, and a C-ITS–based scenario enabling continuous bi-directional information exchange between public transport vehicles and traffic signal controllers.

2.2.1 No prioritization

In the baseline scenario, all vehicles likewise approach the signalized intersection. The traffic light is operating under standard adaptive traffic signal control without any form of public transport priority. Signal phase transitions are determined by general traffic demand. SUMO automatically places detectors on every inbound lane to implement this adaptation. This scenario serves as a reference configuration for comparative evaluation of priority strategies.

2.2.2 Legacy prioritization of public transport

In the legacy priority scenario, a detector based registration point chain and a corresponding priority logic is implemented. The objective is to reproduce conventional public transport priority as typically applied in urban transport today.

As shown in Figure 5, the spatial configuration of the registration point chain for this junction differs by direction. Registration points are modeled explicitly in SUMO by placing induction loop detectors. For northbound vehicles, no advance request is implemented. A main request is triggered before entering the station of Nationalbibliothek, followed by a door contact signal upon completing the passenger exchange. Deregistration is placed just upon entering the intersection. For southbound vehicles, an advance request is generated followed by a main request. Deregistration occurs likewise upon entering the intersection. No door contact signal is placed in this direction, as the station is downstream of the intersection.

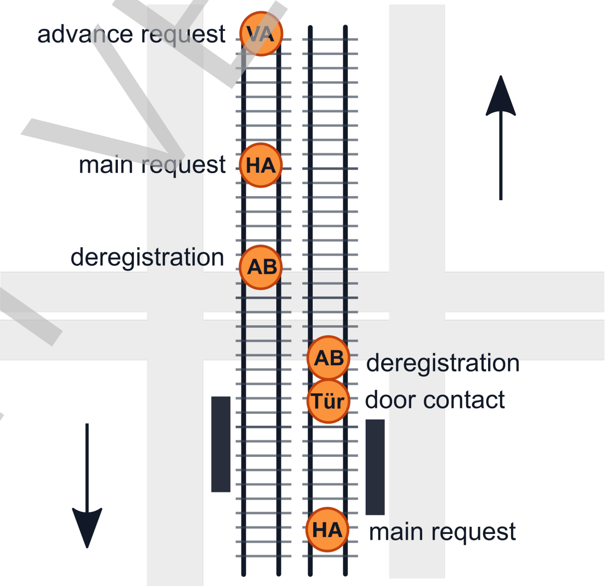


Figure 5. *Placing detectors in SUMO to create a registration point chain*

Based on this registration point chain, the signal controller applies a three stage prioritization logic. Upon first registration of a public transport vehicle, the currently active phase is completed including its regular yellow and all-red transition interval. After that, a transition to the predefined target green phase for the light rail traffic is executed. No phase truncation or forced early termination is applied; the active phase and its clearance phases last up to their nominal times. Once the phase change is initiated, the subsequent green phase is set to the light rail target green phase independent of the next regular phase defined in the traffic light program, allowing intermediate phases to be skipped if required. In SUMO, this behavior is implemented by introducing a condition for a *finalTarget* within the traffic light logic. Once the vehicle is detected at deregistration, phase skipping is deactivated.

Upon activation of the main priority request, a green extension mechanism is enabled. Once the target green phase has been established, it is maintained until deregistration of the public transport vehicle. This prevents premature termination of the

PREPRINT VERSION

target green phase immediately before the train arrives. Holding the green is realized via TRACI by extending the phase duration until the next simulation step until deregistration of the train or until a maximum duration is reached. We use the standard maximum duration of this phase (50 s).

Third, upon activation of a door contact signal, applied exclusively to northbound rail vehicles, a fixed travel time of 8 s between completion of passenger exchange and arrival at the intersection is assumed. If the controller is not already in the target green phase at the time of door closure, the currently active phase is terminated earlier but in compliance with its defined yellow and red clearance intervals, followed by a transition to the target green phase to ensure arrival under green conditions. This enforcement mechanism is likewise implemented using TRACI.

Once the deregistration occurs, the prioritization process is terminated. After that, the traffic light is running the regular program.

Throughout the legacy scenario, communication is strictly uni-directional from the vehicle to the traffic signal controller. No feedback from the controller to the vehicle is assumed. Consequently, the TRACI commands *NextTLS* and *NextSwitch* are not used for this implementation, and the vehicle has no access to information on the current phase or remaining signal phase durations.

Overall, this implementation aims to reproduce the conventional registration point chain model for public transport priority using phase skipping and green extension, thereby representing a realistic legacy reference configuration.

2.2.3 Prioritization of public transport with C-ITS TSP

In our C-ITS TSP implementation, a priority request is generated by the rail vehicle in approach to the intersection at every simulation step. In this scenario, we do not use any detectors or a registration points at fixed locations but we assume a continuous bi-directional information exchange between the vehicle and the traffic light controller. Therefore, we leverage the information provided by the traffic light controller about the current phase and the time until the next switch.

The created priority request is CAM-like. It contains the current vehicle state (position and velocity) and a continuously updated estimation of its arrival time (ETA) at the intersection. To calculate the arrival time, we consider whether there is another stop scheduled before the intersection:

$$ETA = t_{untilStop} + t_{dwellTime} + t_{stopToIntersection}$$

Additionally, deceleration and acceleration before and after the stop have to be taken into account. If there is no stop ahead, the estimated arrival time can be calculated more simple by dividing the distance by the current speed.

To implement the feedback channel from the traffic light, we use the TRACI functions and query the current state (phase and signals) and the timing until the next switch. This resembles a SPAT-like message of the traffic light. Since we have an adaptive traffic light, the *NextSwitch* of the traffic light is a moving target. So to estimate not only the current phase but all subsequent phases until we reach our target green, we save the duration of the last cycle (assuming that traffic has not changed so much since then). From the past cycle durations, we calculate a timeTilGreen (TTG) estimation.

PRE-PRINT VERSION

The priority control logic follows the two established signal priority mechanisms of red truncation and green extension. The intervention decision is based on a continuous comparison between the predicted train arrival and the predicted activation time of the target signal phase (in this case phase 0).
At each simulation step, the following quantities are computed:

- ETA: predicted time until the train reaches the stop line,
- TTG: predicted time until phase 0 becomes active,
- e = ETA-TTG: temporal mismatch between arrival and green onset.

The mismatch e directly determines the implemented priority intervention. If $e < 0$, the start of phase 0 needs to be advanced, if $e > 0$, the train is predicted to arrive after the green has already started. To balance priority service and other traffic, a hierarchical two-stage intervention strategy is implemented.

In the first stage, when the vehicle is still at a larger upstream distance (i.e., ETA sufficiently exceeds TTG), a moderate temporal adjustment of the signal plan is performed within admissible phase duration bounds. The start of the target green phase is shifted toward the predicted ETA. Adjustments are limited to small modifications of phase durations to maintain traffic flow. This stage aims to achieve temporal synchronization without abrupt control changes. This stage is especially relevant if $e > 0$. In the implemented signal program, phase 0 is preceded by phase 8 (yellow transition) and phase 9 (all-red). Since phase 8 and 9 represent safety-critical clearance intervals, they remain unchanged. Consequently, advancing phase 0 can only be achieved by shortening already in phase 4 or 7.

In the second stage, a late adjustment is performed. When the vehicle approaches closer and an alignment has not been sufficiently achieved. In this case, we can still enforce a green extension if the target phase is slightly missed. This ensures passage of the priority vehicle without stopping, provided that other TLS constraints are satisfied.

2.2.4 GLOSA service in the C-ITS scenario

Additionally, in the C-ITS scenario, we activate the GLOSA service. GLOSA allows for an optimal approach upon a red signal. When signal timing information is available, it can be exploited not only for traffic prioritization but to reduce stop-and-go behavior. So if the target phase is off by a few seconds, then it makes sense to approach the intersection more slowly to avoid a complete stop. We have to note that this may also affect the TSP service as a changed speed changes the estimated time of arrival.

SUMO has a built-in GLOSA device for this, which we activate for the rail vehicles. At each approach step, SUMO evaluates whether a moderated speed (between the permissible speed limit and a predefined minimum speed) would allow the vehicle to reach the intersection within the green phase. If such an adjustment enables a timely arrival, SUMO temporarily reduces the *speedFactor* to delay the approach accordingly. Conversely, if a speed reduction would not result in arrival during a suitable green phase, no modification is applied and the vehicle continues with regular speed.

We try a maximum range for the GLOSA device to become active of 300 m and of 500 m before the intersection (default 100 m). There may be no rail signals within the GLOSA range, because the algorithm is always working towards the next upcoming signal. As trains may not exceed the speed limit, we only allow for a speed reduction. As a minimum speed, we define 5 km/h. This makes sense especially for leaving the station just in front of the intersection.

PRE-PRINT VERSION

2.3 SUMO configuration

We set the duration of simulation to 3 hours (10.800 s) plus simulation steps needed for all vehicles to leave the simulation after that. So the duration of the simulation may vary depending on the amount of congestion.

Heavily delayed vehicles are by default removed or teleported after a certain time. Since we especially want to examine the time loss resulting from signal delay and congestion, it is important to deactivate the teleports (-1).

We enable the following simulation output from SUMO:

- Tripinfos: Information on every journey of every vehicle in the simulation (start and end time and place, duration, waiting times, time loss and total stopping duration).
- TLS output: Traffic light phases over time.

Furthermore, we run and control the simulation via TRACI:

- This allows for repeated simulation runs of the same scenario (10 runs/scenario). We regenerate the random car and bicycle traffic using a distinct random seed while light rail and bus operations remain schedule-based. Additionally, we add a random offset to the traffic light program. This generates slightly different situations when approaching the intersection and thus the possibility for a statistical analysis.
- We use TRACI to query information about the implemented services which is not obtainable via XML output files. We create a Logger for TSP and GLOSA data.
- We use TRACI to interact with the simulation to implement the priority mechanisms and to set traffic light phases and durations.

3. Results

In the following, the results of the baseline and priority scenarios are presented and compared using the selected performance metrics.

3.1 Performance metrics

We base our analysis on two main performance metrics:

- *TimeLoss* quantifies the additional travel time relative to the vehicle's optimal trajectory along its intended route. Scheduled dwell times and the associated deceleration for planned stops are excluded. The metric therefore captures only unplanned speed reductions, such as stopping at an intersection, decelerating for a red signal, or queuing due to congestion. Since rail vehicles operate on segregated tracks in this scenario and are not subject to congestion, the SUMO *timeLoss* variable closely approximates signal delay.
- *WaitingCount* denotes the number of unscheduled stops along the route. For rail vehicles, this value should ideally be zero if signal priority is granted effectively.

3.2 Analysis of baseline scenario

The baseline scenario without public transport priority serves as the reference configuration for evaluating delay effects under standard adaptive signal control.

PRE-PRINT VERSION

At this intersection, vehicles exhibit time loss characterized by a pronounced right-skewed distribution (see Figure 6), reflecting signal-induced delays with occasional extreme values. These extremes mainly occur when vehicles narrowly miss the green phase and consequently incur nearly a full signal-cycle delay. Solid lines indicate the mean value and dashed lines the median value. As demand increases, the proportion of vehicles experiencing little or no delay decreases, and the distribution becomes more strongly right-skewed.

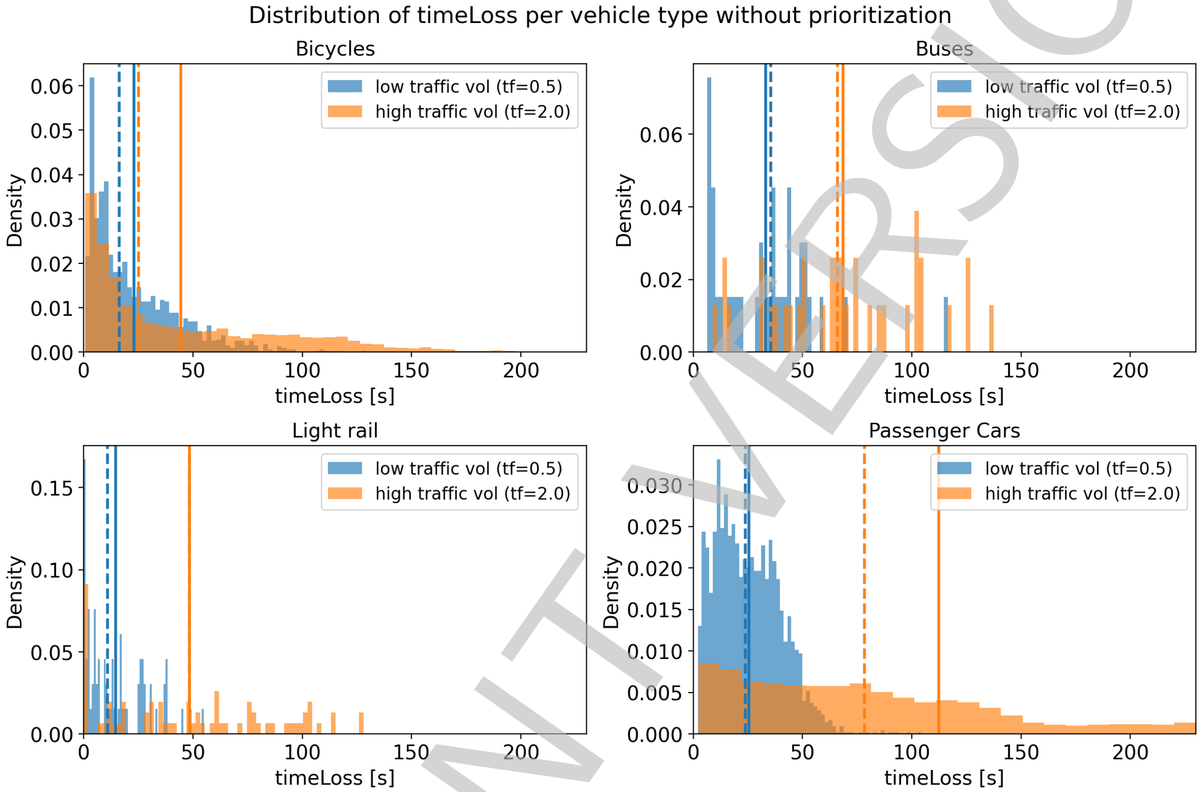


Figure 6. *Distribution of time loss across vehicle types without prioritization*

Overall, similar patterns are observed across all traffic modes, although total vehicle counts differ. Under low traffic conditions (tf=1.0), the median time losses amount to 16.17 s (bicycles), 35.41 s (buses), 10.84 s (light rail vehicles), and 23.77 s (passenger cars). With increasing traffic demand (tf=2.0), the mean time loss rises substantially, particularly for passenger cars (78.29 s), which experience additional congestion-related delays beyond the signal delay. In contrast, light rail vehicles show comparatively lower mean time loss (48.29 s), as they operate on independent tracks.

We investigate the time loss of the light rail vehicles by direction, see Figure 7. The time loss is higher for the northbound direction which has the station just before the intersection. The median time loss amounts to 14.39 s, while the southbound direction shows lower values with a median of 5.79 s (tf=1.0).
Further, we find that short signal phase durations negatively affect rail vehicles, which already require longer yellow phases due to their braking characteristics. As a result, the time loss is higher or similar under low traffic compared to medium traffic conditions. With increasing vehicular traffic demand, the proportion of vehicles experiencing significant time loss rises. The delay distribution becomes more dispersed, with a greater number of high delay outliers caused by vehicles waiting for a full signal cycle.

PREPRINT VERSION

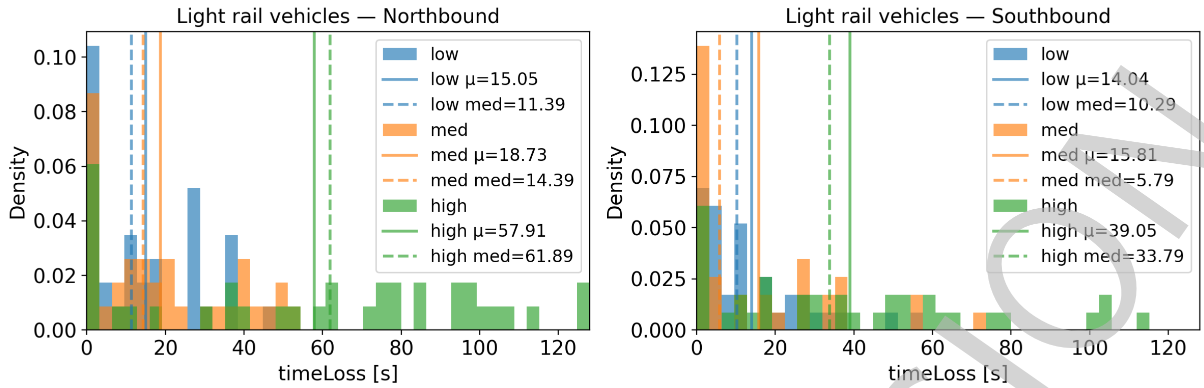


Figure 7. *Time loss of light rail vehicles for different traffic levels and directions*

Overall, the baseline scenario reveals substantial and direction-dependent delay effects under adaptive signal control without public transport priority. These results provide a consistent reference for quantifying both the efficiency gains and distributional changes achieved through subsequent priority strategies.

3.3 Analysis of prioritization mechanisms

We implemented two distinct prioritization mechanisms: the conventional approach based on a registration point chain and the C-ITS TSP service. Both methods are evaluated against the baseline scenario and compared directly with each other.

In Figure 8, the approach of southbound vehicle "pt_subway_U5_1:22" towards the intersection is depicted. The stop line is indicated by the dotted blue line. Four different TLS bands are shown: The first TLS band illustrates the signal states over time without prioritization, the second band under the legacy prioritization mechanism, the third under the C-ITS with only the TSP algorithm and the fourth under the C-ITS algorithm with TSP and GLOSA. They all have the same TLS program, but as different mechanisms act on them, they show different timings. The vehicle trajectory is shown in blue (baseline without prioritization), orange (legacy prioritization), blue (C-ITS TSP), red (C-ITS TSP+GLOSA); three trajectories are nearly identical and thus plotted on top of each other, differing only in the final segment. The vehicle in the C-ITS TSP scenario may pass without stopping (but we do see a slow down). For the legacy and no prioritization scenario, the line along the stop line indicates a waiting time at the

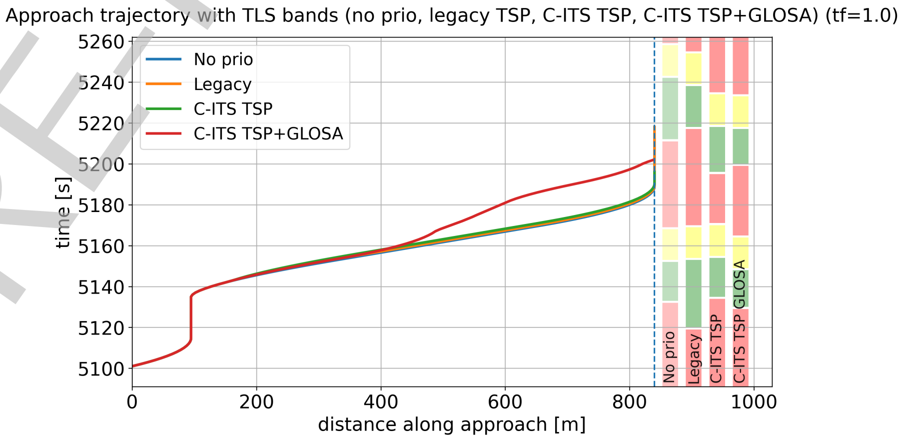


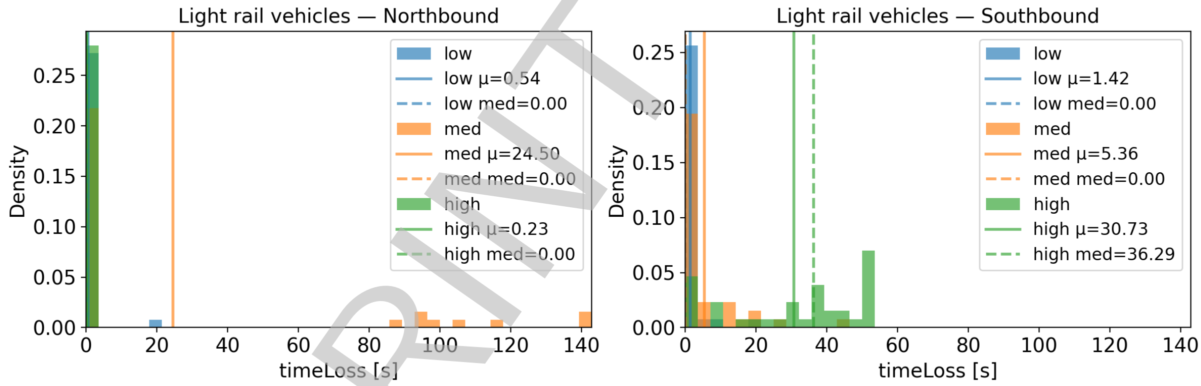
Figure 8. *Approach of southbound vehicle to the stop line and the TLS bands over time for the baseline, legacy and C-ITS TSP scenario*

PRE-PRINT VERSION

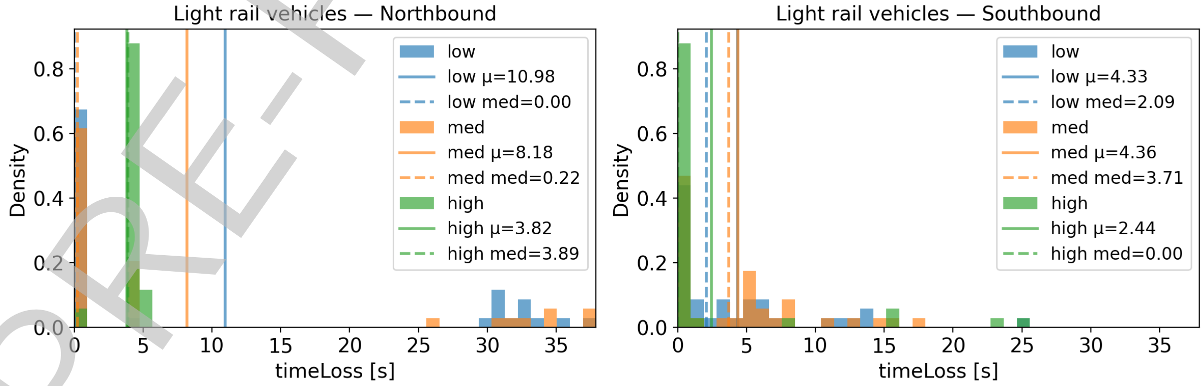
intersection. The fourth trajectory shows the slow down by the GLOSA algorithm to reach the intersection at target green. Therefore, GLOSA also influences the behavior of the TSP algorithm. By reducing or eliminating the temporal offset to the target green phase in advance, the need for active TSP interventions is reduced. This Figure presents an illustrative example. Its outcome differs across vehicles, as they arrive at different times and thus see different traffic signal states; accordingly, both the applied priority strategy and its effectiveness vary between cases.

The two subplots in Figure 9 compare the distribution of time loss for rail vehicles by direction (northbound and southbound) under different demand levels (low, medium, high) and under both control strategies: the legacy prioritization and the C-ITS TSP.

Legacy prioritization performs very well for the northbound approach across all demand levels, with zero medians zero and only small increases in mean delay as demand rises. This may be attributed to the door signal which directly triggers the green phase in short approach. However, southbound performance under legacy control deteriorates with increasing demand: for medium demand, we see delays up to 25 s, and high demand leads to much higher delays (medians at 36.29 s). Under C-ITS, northbound delays are generally moderate and relatively concentrated around 4–6 s with median close to zero but several large outliers inflating the mean. Southbound exhibits stable and overall moderate delays, with particularly strong performance at high demand where the median timeLoss is still zero. The approach to the intersection in the SUMO scenario is significantly shorter for the northbound scenario, this may yield



***(a)** Time loss of light rail vehicles with legacy prioritization*



***(b)** Time loss of light rail vehicles with C-ITS TSP*

***Figure 9.** Time loss by direction and traffic factor*

PRE-PRINT VERSION

in insufficient time for an early adjustment of phase timings and thus worse results for the northbound direction.

In summary, legacy prioritization is highly effective northbound but performance decreases in the southbound southbound and with increasing demand, whereas C-ITS provides substantially more robust and balanced performance. In summary, all histograms indicate a strong directional asymmetry resulting from topological influence on the prioritization.

For further analysis, we assess the reduction in signal-induced delay and evaluate the impact on non-prioritized traffic at the intersection. Figure 10 presents the per-vehicle change in time loss (delta) relative to the baseline for the legacy scenario and the C-ITS scenario (TSP+GLOSA) for tf=1.0, distinguishing between rail vehicles and other traffic. The y-axis is shown with a logarithmic scale, enabling the simultaneous visualization of the high vehicle counts around a delta close to zero and the comparatively rare but extreme outliers.

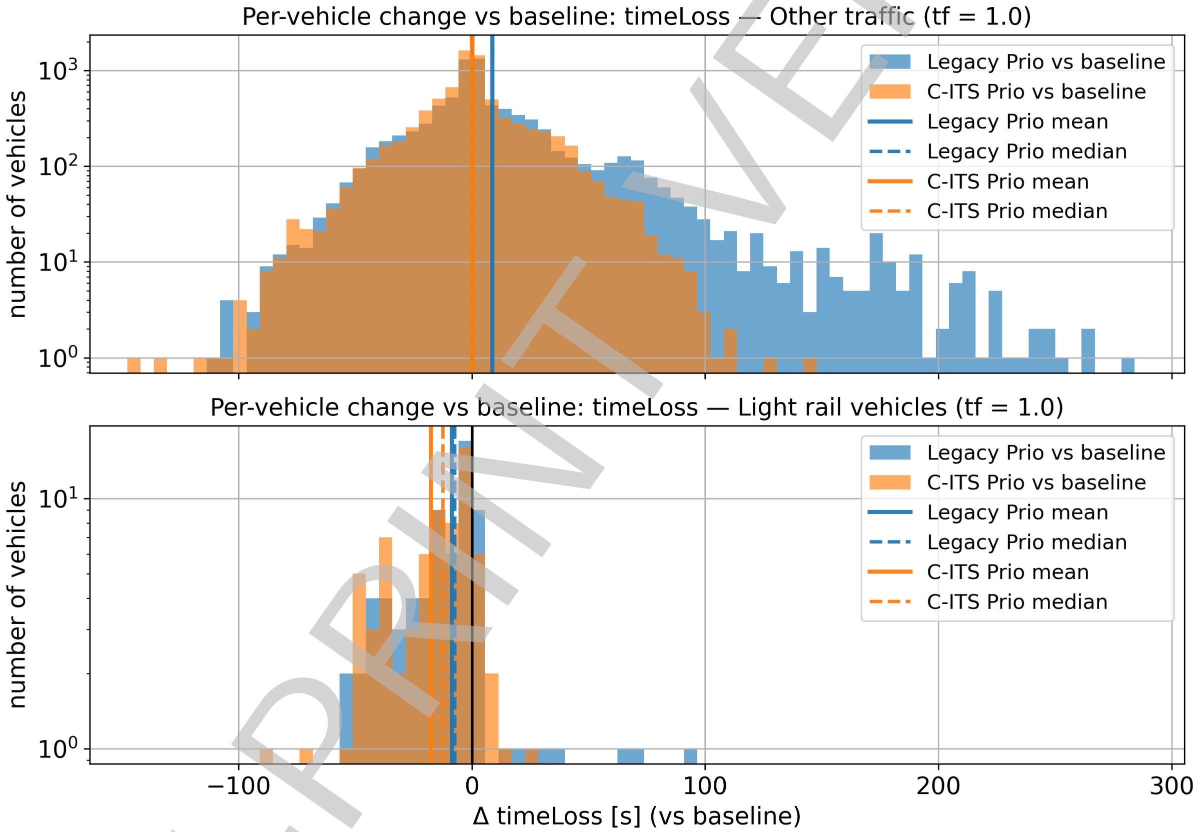


***Figure 10**. Comparison of time loss for light rail vehicles and other traffic (with a logarithmic scale)*

For rail vehicles, both prioritization strategies reduce the time loss significantly: the legacy mechanism yields a mean delta of -8.60 s (median -7.24 s), while C-ITS further improves performance to a mean of -17.45 s (median -12.42 s). For other traffic, the legacy approach results in an increase of time loss (mean +8.77 s, median +0.35 s), whereas the impact in the C-ITS scenario is significantly lower (mean 0.28 s, median -0.14 s). Notably, the distribution for other vehicles in the legacy prioritization scenario exhibits a pronounced right-skewed tail indicating some vehicles experiencing substantial delay; this tail is absent under C-ITS, suggesting a mitigation of extreme outliers in the non-prioritized traffic while maintaining improved performance for the prioritized vehicles.

PRE-PRINT VERSION

3.4 Analysis of GLOSA service

To determine when the GLOSA service is active, we monitor the *speedFactor*. We observe that the activation range is a critical parameter when applying GLOSA to rail vehicles. With a range of 300 m, the impact of the GLOSA service is only marginal since the braking distance on approaching a red signal is approximately 200 m, thus braking typically begins shortly after GLOSA activation. In contrast, increasing the range to 500 m enables the GLOSA service to operate effectively also for rail vehicles. In this case, the waiting count decreases substantially, particularly in the southbound direction.

For the northbound direction, a GLOSA activation before the station does not result in a successful modification of arrival time at the intersection due to the intermediate dwell time. After departing from the station, the remaining travel time to the intersection is very short, allowing only for marginal adjustments. In most cases, the train either departs during the extended green phase or the *maxDur* constraint has already been reached. In the latter case, the vehicle must wait for the next full signal cycle and stop at the intersection regardless of the GLOSA strategy. Under these conditions, a Green Light Optimal Dwell Time Advisory (GLODTA) approach may be a better solution.

The southbound direction shows significantly greater effects from GLOSA, as no station stop is located directly upstream of the intersection. When the train would arrive slightly too early for the green phase, the algorithm reduces the speed to align with the subsequent target green, as illustrated in Figure 11. The vehicle does not need to stop; however, the speed profile during the approach is highly volatile, which may negatively affect passenger ride comfort as well.

GLOSA shall prevent the stop-and-go behavior, therefore we investigate on the waiting count. Figure 12 shows the amount of trains that had to stop at the traffic light.

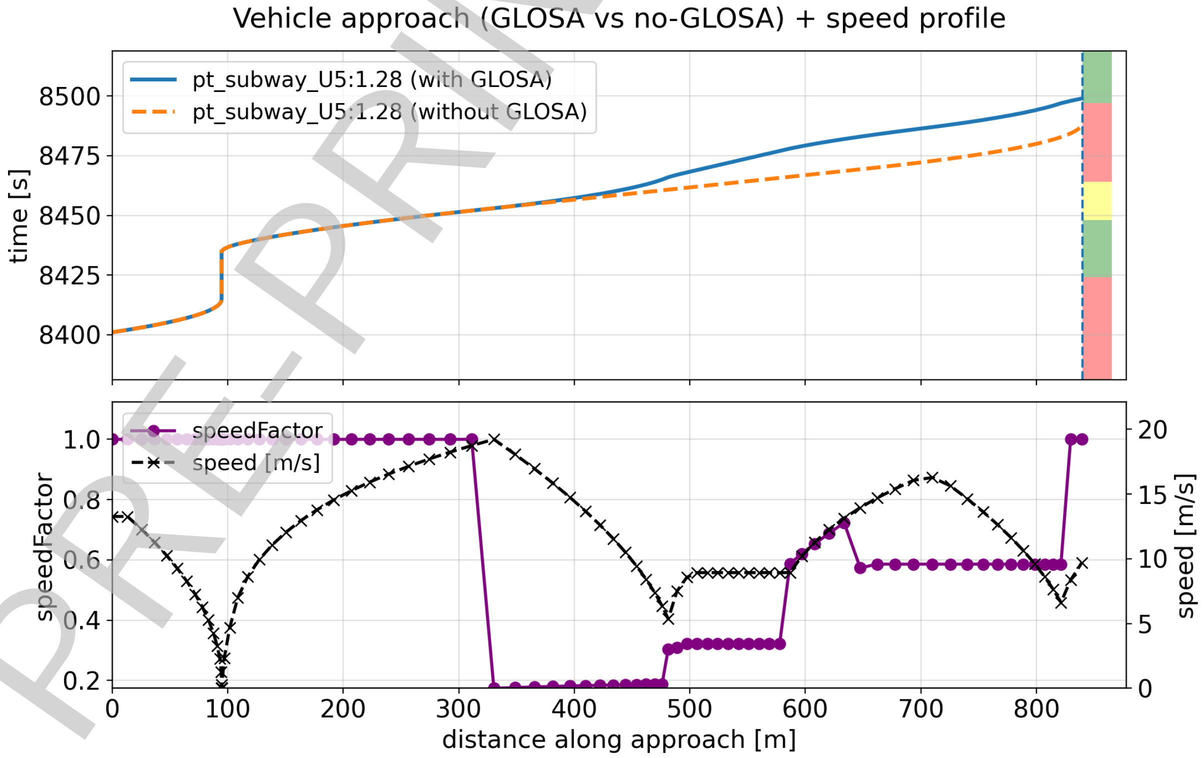


Figure 11. *Approach to the intersection of southbound vehicle U5:1.28*

PRE-PRINT VERSION

PRE-PRINT VERSION

Out of 72 trains in a simulation run in the baseline scenario, 43 trains had to stop. Both directions are quite evenly affected. In the legacy scenario, the amount of vehicles which have to stop is reduced to 14 and we see that southbound vehicles have to stop more often than northbound vehicles. In the C-ITS scenario, we see a further reduction to 13 stops. And with activation of the GLOSA service, only 6 vehicles (all northbound) had to stop at the intersection.

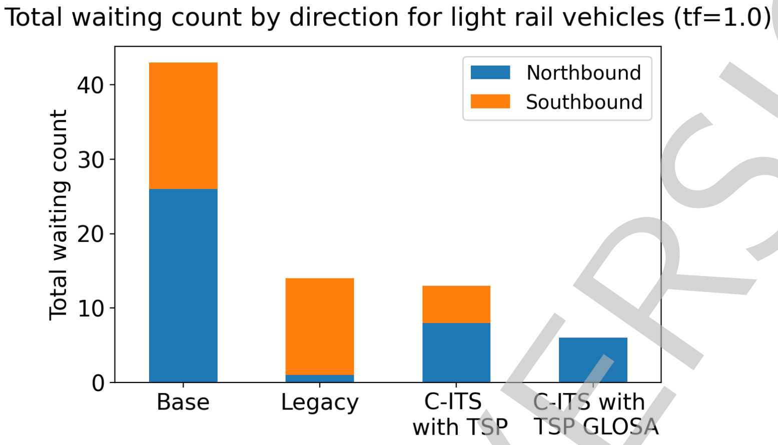


Figure 12. *Amount of trains that had to stop at the traffic light (GLOSA range 500 m)*

3.5 Statistical evaluation

To assess statistical differences between simulation runs, each scenario is executed ten times. We vary traffic and set an offset to the traffic light program ensuring that vehicles encounter varying conditions when approaching the intersection.

Figure 13 shows a simulation cloud for all three scenarios and repeated simulation runs. One dot represents one simulation run. For each vehicle type, we plot the mean value which reflects performance (in terms of added delay) and the coefficient of variation (CV, σ/mean) which captures relative variability. Lower values in both dimensions are desirable.

Most importantly, we see no significant statistical differences between simulation runs within each scenario. We have to note that the amount of cars and bicycles are higher, thus any prioritization measure will affect the mean and CV of them less as only few vehicles that are present in that very moment are affected. Therefore they show a more stable placement in the plot.

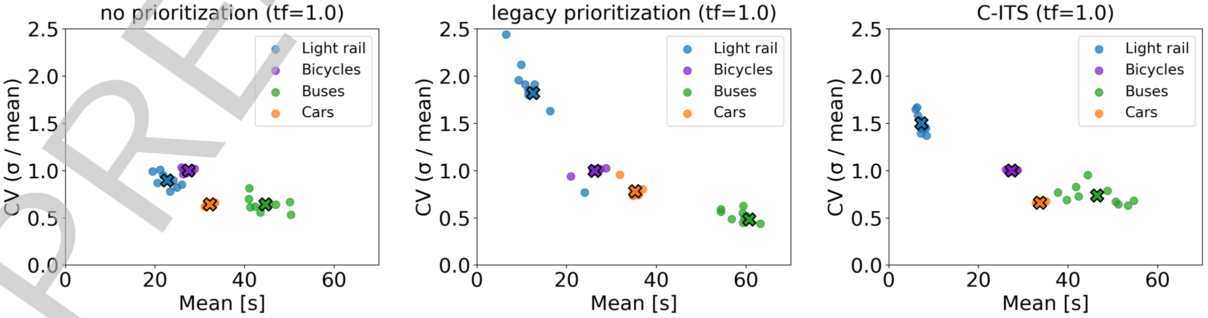


Figure 13. *Simulation cloud of time loss for different vehicle types across repeated simulation runs*

In the no prioritization scenario, all modes exhibit a relatively balanced performance. All vehicle types show modest mean values and also modest variability. Under legacy prioritization, a substantial reduction in mean values for light rail vehicles is achieved, indicating effective prioritization. However, this is accompanied by a pronounced increase in CV, revealing significantly increased variability. At the same time, buses experience increased mean values, indicating negative spillover effects. Cars and bicycles show only a small increase in the mean value which may also be attributed to the amount of vehicles present in the simulation. The C-ITS scenario preserves the low mean values for light rail vehicles while noticeably reducing its CV compared to the legacy approach, indicating improved reliability and less variability. For the buses, we notice a higher spread in the mean value with values high than in the baseline but less than with the legacy prioritization.

In summary, these plots confirm the results that we obtained earlier. The legacy prioritization obtains good results for the prioritized traffic, while the C-ITS approach achieves efficiency gains for the light rail system while reducing negative effects on non-prioritized modes.

4. Discussion

4.1 Shortcomings of the implemented scenario

The modeled northbound approach to the intersection is very short as it was only designed to meet one stop to stop relation each. To fully leverage C-ITS–based early signal timing adjustments, a longer approach section should be modeled.

Traffic is generated randomly between fringe origins and destinations without specific routes. As a result, demand is distributed uniformly, although the lane configuration and intersection geometry are designed for uneven directional flows. The East-West traffic is much stronger than North-South traffic. Also, there is a comparatively high demand from East to North in the simulation, but only a single lane is available, leading to congestion that also impacts bus operations. Implementing weighted routes would enable a more realistic representation of traffic.

Additionally, the scenario is based exclusively on publicly available data. No traffic count data were available to calibrate representative demand, nor do we have detailed information on the implemented signal control logic or existing public transport prioritization. Consequently, the model relies on assumptions derived from currently applicable state of the art.

4.2 Operational findings

The operational analysis demonstrates that signal priority substantially improves light rail traffic performance compared to the baseline, but its effectiveness strongly depends on direction and demand level. Without prioritization, trains experience pronounced right-skewed time loss distributions, indicating structural signal-induced delay. Both priority strategies significantly reduce time loss and the number of unscheduled stops; however, their impacts differ. The legacy mechanism achieves very low delays in the northbound direction, primarily due to direct green extensions triggered by the door signal, but its performance deteriorates southbound with increasing demand.

In contrast, the C-ITS approach provides more balanced and robust behavior across demand levels while also reducing adverse effects on non-prioritized traffic. Overall, the

PRE-PRINT VERSION

results indicate that cooperative, anticipatory strategies enhance system robustness rather than solely maximizing delay reduction for the prioritized vehicles.

4.3 Further work

So far, the analysis considers only the impact of light rail prioritization on buses and does not model buses generating priority requests of their own. Since buses typically do issue such requests incorporating bus priority requests would yield more representative results and allow for a clearer assessment of the impacts on trains, especially in conflicting situations.

The implemented priority request currently resembles a CAM-like message. In a mature C-ITS deployment, Signal Request Messages (SRM) are used, which additionally account for vehicle occupancy and delay. These attributes are not yet modeled in our SUMO scenario. Extending the simulation to include passenger loads and delay states would therefore be a logical next step, enabling priority or preemption strategies that adapt dynamically to the actual operational relevance of each vehicle.

Future work should investigate the addition of a GLODTA service for dwell time control at the station. This means dynamically adjusting departure times based on predicted signal states. Whenever a green phase cannot directly be set or the impact on other traffic is assumed as too high, the vehicle should spent the waiting time at the station instead of the stop line.

5. Conclusion

This study evaluated signal-related delay for rail operations at a signalized intersection using a SUMO-based microscopic simulation. A baseline scenario without priority was compared to two scenarios with prioritization: a conventional registration-point-based approach and a C-ITS-based TSP service combined with GLOSA. The analysis focused on signal-induced time loss and waiting count across different demand levels.

The baseline scenario showed right-skewed delay distributions. Both priority strategies significantly reduced delays of light rail traffic compared to the baseline. The legacy approach performed very well northbound, achieving near-zero median delays, but deteriorated southbound under increasing demand. In contrast, C-ITS provided a more balanced and robust performance. While not consistently outperforming legacy priority, it reliably prevented the extreme delay escalation and reduced negative impacts on general traffic. Overall, the results indicate that C-ITS not only improves delay reduction for prioritized vehicles, but more importantly it enhances overall system robustness and mitigates adverse impacts on surrounding traffic flows.

Future work should further extend the simulation to the intended C-ITS target architecture by incorporating additional operational attributes such as vehicle delay states and occupancy levels, as well as a GLODTA service. The required functionality can be implemented within the existing SUMO framework. This extension would enable a more comprehensive assessment of C-ITS, moving beyond delay minimization for light rail traffic towards an evaluation of the overall traffic system.

Data availability statement

All used data is obtained from public sources. Topological data is based on OpenStreetMap, refined with GoogleMaps and verified as far as possible during a site visit.

PRE-PRINT VERSION

Train and bus schedules are published by RMV. We do not have any data on vehicle counts, therefore they are estimated and varied. The TLS program is based on SUMO defaults with some refinements for the light rail traffic.

Underlying and related material

All code created for this analysis is available at GitHub: [12].

Author contributions

M.Sc. Paula von der Heide: conceptualization, investigation, methodology, software, formal analysis, visualization, writing original draft, writing review & editing.
Prof. Dr.-Ing. Lars Schnieder: coceptualization, supervision, writing review & editing.

Competing interests

The authors declare that they have no competing interests.

Acknowledgments

We give credit to the developers of SUMO who have provided the opportunity to work with an open-source simulator.

This text was created with the assistance of ChatGPT to rephrase and enhance its readability. Additionally, ChatGPT was used to support with scripting Python.

PREPRINT VERSION

References

[1] K. J. Schmidt, N. Steinmetz, and M. Margreiter, “Bus Priority Procedure for Signalized Intersections Based on Bus Occupancy and Delay,” *SUMO Conference Proceedings*, vol. 5, Jul. 2024, ISSN: 2750-4425. DOI: 10.52825/scp.v5i.1111.

[2] M. Seredynski, B. Dorronsoro, and D. Khadraoui, “Comparison of Green Light Optimal Speed Advisory approaches,” in *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, The Hague, Netherlands: IEEE, Oct. 2013, ISBN: 978-1-4799-2914-6. DOI: 10.1109/ITSC.2013.6728552.

[3] M. Gay et al., *Nutzung der C2X-basierten ÖV-Priorisierung an signalisierten Knotenpunkten: Applicability of V2X for transit signal priority* (Berichte der Bundesanstalt für Strassenwesen V, Verkehrstechnik Heft 353), de. Bremen: Fachverlag NW in Carl Ed. Schünemann KG, 2022, ISBN: 978-3-95606-646-7.

[4] D. Vallée, B. Engel, and W. Vogt, Eds., *Stadtverkehrsplanung Band 3: Entwurf, Bemessung und Betrieb*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2021, ISBN: 978-3-662-59696-8 978-3-662-59697-5. DOI: 10.1007/978-3-662-59697-5.

[5] Forschungsgesellschaft für Straßen- und Verkehrswesen and Forschungsgesellschaft für Straßen- und Verkehrswesen, *Hinweise zu Bevorrechtigungsmaßnahmen für den ÖPNV im städtischen Verkehrsmanagement* (FGSV W1 361), de, Ausgabe 2018. Köln: FGSV Verlag GmbH, 2018, ISBN: 978-3-86446-212-2.

[6] C. Jobst, “C-ITS für die Lichtsignalsteuerung – Status Quo und Ausblick aus Sicht das Planungsingenieurs,” de, 2024.

[7] Lars Schnieder and Lennart Asbach, “Einsatz von V2X zur Beschleunigung in Stadtbahnsystemen,” Jan. 2022.

[8] VDV, “VDV-Mitteilung 4022 Beschleunigung von öPNV-Fahrzeugen an Lichtsignalanlagen mit CITS – Migration des öPNV von „morgen“ im Umfeld von Lichtsignalanlagen,” Tech. Rep., 2023. Accessed: Sep. 22, 2025. [Online]. Available: https://www.vdv.de/downloads/5494/4022%20MDK/forced.

[9] Christian Schmidt, *Digital Train Control System Frankfurt - Symbiose CBTC und C-ITS*. Accessed: Jul. 11, 2025. [Online]. Available: https://its-mobility.de/wp-content/uploads/III_02_Schmidt_VGF_C-ITS-Forum_2024_C-ITS-Forum_2024.pdf.

[10] VGF, *VGF Fahrzeugtypen Flyer U5-Wagen*, Jul. 2021. Accessed: Jun. 17, 2025. [Online]. Available: https://www.vgf-ffm.de/fileadmin/VGF/Die_VGF/Fuhrpark/Documents/VGF_FB_20_06_Fahrzeugtypen_Flyer_RZ3-U5-Wagen_Web_U5_V2.pdf.

[11] P. von der Heide and L. Schnieder, “A SUMO-Based Study of Urban Rail operations on Frankfurt´s Corridor A,” in *5. International Railway Symposium Aachen*, Nießen, Nils, Schindler, Christian, and R. Pfaff, Eds., Artwork Size: pages 762 Seiten : Illustrationen, Tabellen, Diagramme Publisher: RWTH Aachen University, vol. IRSA 2025, 2026. DOI: 10.18154/RWTH-2026-00357. Accessed: Mar. 10, 2026.

[12] Paula von der Heide, *Simulate Urban Rail in SUMO*, Braunschweig, Jun. 2025. [Online]. Available: https://github.com/pvonderheide/simulate_urban_rail_in_sumo.

PRE-PRINT VERSION