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The role of c-its in reducing emergency service travel time through intelligent traffic light systems in microsimulation models using PTV vissim

Merel Smets

Thesis presented in fulfillment of the requirements for the degree of Master of Transportation Sciences, specialization Transport Policy and Planning

SUPERVISOR :
Prof. dr. ir. Ansar-Ul-Haque YASAR

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The Role of C-ITS in Reducing Emergency Service Travel Time through Intelligent Traffic Light Systems in Microsimulation Models Using PTV Vissim

Merel Smets[a], Prof. dr. ir. Ansar Yasar[b], Imran Nawaz[c], Erik Vandermeersch[d]

[a]Hasselt University, Transportation Research Institute (IMOB), Belgium
[b]Transportation Research Institute (IMOB), Belgium
[c]Transportation Research Institute (IMOB), Belgium
[d]Senior Specialist (Sweco) Belgium

Abstract: The research contains a microsimulation analysis with the implementation of intelligent traffic lights on emergency vehicle travel times. To analyze the effect on general traffic performance and emergency vehicle prioritization, the PTV VISSIM tool was used to simulate a major signalized intersection at the ring road of Leuven. The baseline model represents current traffic conditions and signal timings based on real traffic data and smart traffic light signal programs. Three follow-up measurements were modeled with intelligent traffic lights, varying the emergency vehicle's turning direction (left, right, and forward). Results indicate that intelligent signal control significantly reduces emergency vehicle travel time across all directions. Meanwhile, the impact on general traffic is direction-dependent. Vehicles traveling in the same direction as the emergency vehicle experience minimal delay, while those on opposing or conflicting approaches show travel time increases. The research emphasizes the importance of intelligent traffic lights for the travel time of emergency vehicles. The findings underscore the necessity of integrating cooperative intelligent traffic systems into urban infrastructure to enhance emergency response efficiency.

Highlights:

- Signal preemption reduced emergency vehicle travel time by up to 37.01%
- Emergency vehicle travel time reduced by an average of 27.88 seconds
- Conflicting traffic delays rose up to 47.56 seconds
- Average queue length increased by 13.44 meters on non-priority roads
- Long-range priority requests key to effective emergency vehicle preemption

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Keywords: PTV Vissim; Microsimulation modeling; Intelligent traffic lights; Travel times emergency vehicles

1. INTRODUCTION

Urban road networks, particularly in large metropolitan areas, are undergoing rapid and continuous growth in the number of vehicles on the road, leading to increased traffic congestion. In Flanders (Belgium), 2024 set a record for traffic congestion, with 60 days surpassing 200 kilometers of traffic jams (Agentschap Wegen & Verkeer, 2025).

Thesis Supervisor: Ansar Yasar, Co-supervisor/Mentor: Imran Nawaz

Traffic congestion significantly impacts emergency vehicles' travel time, impeding emergency vehicles' ability to reach incident locations swiftly and reliably. This has been widely recognized as a critical factor affecting travel time, with urban congestion contributing to an average delay of nearly 10 minutes (Griffin & McGwin, 2013).

Emergency vehicles refer to any motor vehicle used by emergency services, such as ambulances, fire trucks, and police cars, deployed in emergencies (Zerroug et al., n.d.). Emergency vehicles are designed and equipped to respond rapidly to emergency calls, providing essential medical, firefighting, law enforcement, or rescue services. Travel time is the time required to travel from the starting point of the emergency vehicles to the location of an emergency event (Oliveira & Duarte, n.d.).

Medical emergencies require immediate attention. In these critical situations, every second is crucial (Zerroug et al., n.d.). Therefore, travel time is a vital performance indicator for emergency response units (Nuyttens, 2023).

The more expeditious and efficiently injured individuals receive care, the greater the chance of survival (Elvik et al., 2009), the greater the chance of less severe consequences (European Commission, 2019), and the greater the chance of a full recovery (Elvik et al., 2009). A report from the European SafetyNet project on road safety performance indicators identifies three critical periods during which traffic-related injuries can result in fatalities. The first critical period occurs in the immediate seconds and minutes following the injury. The second, known as the 'golden hour,' occurs within one to two hours post-injury. The third period spans the days and weeks after the initial incident (SafetyNet, 2005). Emergency vehicles' travel time will significantly impact the second period, the golden hour. In the first period, even a rapid response time can rarely prevent a fatal outcome, and the survival prospects in the third period rely more heavily on the quality of hospital care (Nuyttens, 2023). According to research findings in Germany, the chances of survival for an accident victim increase by 40% if an emergency vehicle can arrive 4 minutes faster. This statistic underscores the critical importance of minimizing travel times for emergency vehicles (*Asfinag*, n.d.).

Article 37.4 of the Belgian road code specifies that a designated priority vehicle can legally proceed through a red traffic signal under specific conditions. This exemption applies exclusively when the vehicle's warning system is activated. Furthermore, the vehicle must come to a complete stop prior to entering the intersection and may only proceed if doing so does not pose a safety risk to other road users.

Per road code Article 38, every road user must immediately clear passage and prioritize emergency vehicles as the sound device of an emergency vehicle announces its approach. Committing an offense that directly endangers the safety of others or ignores the order of an authorized person is considered a third-degree offense. The obligation to give way to a priority vehicle, as per article 37.4, is attributable to the fact that the arrival of this vehicle is announced to other road users. This necessitates that the siren be active for a certain period, enabling other road users to hear it and clear it safely without causing accidents (Lokale Politie, 2017).

Although emergency vehicles possess the privilege to disregard certain traffic signals, they significantly present safety concerns. In Europe, an estimated 88,000 traffic accidents involving emergency vehicles occur annually, with 37,900 incidents occurring at intersections. Red-light running is recognized as one of the most hazardous maneuvers for emergency vehicles, contributing to an estimated 164 fatalities each year (Erneberg et al., 2023).

Previous research indicates that implementing green phase preemption at signalized intersections can reduce average travel times by more than 10%. Furthermore, studies demonstrate that granting emergency vehicles priority at intersections enhances safety, decreasing the risk associated with intersection crossings by over 50%. On a broader scale, integrating green phase preemption across Europe can potentially prevent more than 19,000 emergency vehicle accidents annually, ultimately saving hundreds of lives and significantly reducing financial costs for government agencies (Erneberg et al., 2023).

This research examines the impact of green phase preemption on the travel time of emergency vehicles in Leuven, Belgium. Utilizing PTV Vissim, microsimulations are conducted for an intersection along the city's ring road. The research evaluates the implementation of intelligent traffic lights on emergency vehicle travel times and their broader implications for surrounding road users.

Nomenclature

C-ITS	Cooperative Intelligent Traffic Systems
EMVs	Emergency Vehicles
EU KPI	Europe Key Performance Indicators
ETSI	European Telecommunication Standards Institute
iTLC	Intelligent Traffic Light Controller

2. EMERGENCY TRAVEL TIMES: PERFORMANCE BELGIUM

Analysis of the EU KPI 'post-crash care' in Belgium shows that the response times of ambulances in Belgium are noticeably higher than in other European countries. Europe uses a baseline of 90% of responses within 15 minutes, which is not met in Belgium. In 2019, only 72% of interventions were completed within 15 minutes. Considering other percentile ranges, 95% of responses were within 32 minutes, 90% within 24 minutes, 75% within 16 minutes, and 50% within 11 minutes (Nuyttens, 2023). Analyzed among twelve European countries, Belgium had in 2023 the third longest 95th percentile response time, exceeded only by Greece and Sweden (Nuyttens, 2023).

Fire engine travel times in Leuven were significantly higher than the national average travel time in 2020, attributable to increased traffic congestion. At the national level in Belgium, the average response time for fire engine services was 11 minutes and 21 seconds in 2020. Decomposed into 4min 26s departing the station, 6min 55s travel time. The east emergency response zone of Flemish Brabant, including Leuven, has a travel time noticeably higher than the national average at 11 minutes 26 seconds, with 3min 36s departure time and 7min 50s travel time (*Statistieken_hulpverleningszone,* 2020).

In collaboration with the fire department and medical emergency services, the police ensure 24-hour accessibility and availability in Belgium. According to Federal public service inspections of the Federal and Local police in Belgium, data from 2009 indicates that the police responded on average to 50% of urgent calls within 16 minutes, 75% of all calls within 26 minutes, and 90% within 44 minutes. Intervention times consist of several categories. The call-taking time required to register an incident shows that 75% of calls are processed within 3 minutes 30 seconds and 90% within 5 minutes. The dispatch time, which is the period taken to dispatch the intervention team, research indicates that 75% of interventions are dispatched within 4 minutes and 90% within 13 minutes. Finally, the travel time, which is the duration taken for the intervention unit to travel to the incident location, shows that 50% of cases have a travel time of less than 8 minutes, 75% of cases have a travel time of less than 13 minutes, and in 10% of the cases, the travel time exceeds 23 minutes (*AIGpol*, 2009).

3. COOPERATIVE INTELLIGENT TRAFFIC LIGHTS

In 2025, smart traffic light systems remain the most widely used in Belgium, featuring a primary designated traffic direction, with side streets operating on-demand through loop detection mechanisms. These systems follow a vehicle-dependent cycle, incorporating a fixed minimum green duration, which can be extended up to a predefined maximum threshold upon detecting a vehicle. If a vehicle enters the intersection during the extension phase, the green light duration is prolonged.

Conversely, if no vehicle is detected, the green phase terminates. To maintain adaptive functionality, the minimum green time for motorized traffic on Flemish regional roads is typically five seconds (Agentschap Wegen & Verkeer, 2020). The system dynamically adjusts green phases based on real-time traffic conditions, employing Boolean logic to determine whether an extension is warranted depending on vehicle detection status (De Naegel, 2013).

Vehicle-dependent traffic light systems utilize various detection configurations to monitor traffic flow, including inductive loops, radar-based sensors, and optical cameras (video or thermal detectors). However, these systems exhibit limitations regarding vehicle occupancy assessment and queue management (Agentschap Wegen & Verkeer, 2020). One of the most significant drawbacks of vehicle-dependent traffic light schemes is their inability to differentiate between vehicle types. Emergency response units rely on rapid transit through intersections, yet these detection systems predominantly identify standard vehicles. If the detection mechanisms fail to respond swiftly or malfunction, emergency services may experience substantial delays. This unpredictability presents a critical challenge, as prolonged travel times can adversely affect emergency interventions.

Intelligent transportation systems are rapidly transforming how cities manage and optimize transportation networks and are classified under traffic control by improving the utilization and efficiency of existing facilities (Yu et al., 2022).

Belgium is transitioning from traditional smart traffic signals towards advanced intelligent traffic control systems at 250 of the 1,700 traffic light intersections in 2024.

Intelligent traffic lights adapt based on real-time traffic data. Sophisticated software algorithms can then use this data to control and coordinate traffic signals, providing a more efficient management of the entire transportation system. A key feature of Belgium's intelligent traffic lights implementation is cloud-based software-as-a-service (SaaS) to operate the traffic control system (*Mobilitdata*, 2022).

3.1. Data communication and system architecture

The information streams of the intelligent traffic lights used in Belgium are based on C-roads and Talking Traffic standards and protocols. C-roads is a platform for European authorities and road operators to harmonize the development of cooperative intelligent transport systems. Talking Traffic collaborates within the Netherlands to scale out long-range C-ITS (Imec, 2022).

The mobilidata interchange for intelligent traffic light systems is the most critical component of the information chain in Belgium and consists of one interface, MI-interface. The MI-interface is an extended but compatible version of the C-roads basic interface (BI), which is, in essence, a metadata envelope that allows for the exchange of standard ETSI or DatexII messages using the AMQP protocol.

DataexII is a European standard for exchanging traffic and travel information, enabling the standardized exchange between traffic management centers, service providers, and operators, and the AMQP protocol is used for reliable message delivery.

The MI-interface includes a feedback flow for road users or service providers. The public information provider can send information to the Mobilidata interchange, which then the Mobilidata interchange can send information to the external information provider (road infrastructure exchange).

Data is stored in a GDPR-compliant historical archive for monitoring and analysis purposes. The connection of intelligent traffic lights is standardized based on the Talking Traffic program of the Netherlands. It uses the SI protocol, secure interoperability protocol, to ensure reliable communication with the road infrastructure exchange (Mobilidata, 2022).

Emergency services, including medical services, police and fire departments, receive the highest priority. However, traffic lights do not automatically turn green for every approaching emergency vehicle. Safety regulations, such as clearance times, must be respected even at the highest priority level. To ensure safe and efficient traffic management, intelligent traffic lights employ an intelligent traffic control installation (iVRI) to regulate traffic lights dynamically. Each implemented iVRI consists of three (shared) components that interact with each other. The RIS is responsible for maintaining a local dynamic map of the junction, handling C-ITS messages, and maintaining network security for the outside world. Actuating the lights of the signal at an intersection is done by the traffic light controller to prevent unsafe situations. The traffic light controller is comparable to a standard traffic light. The ITSApp is responsible for controlling the traffic flow optimally and determining the best signal phase and timing values. The central service architecture of the iTLC is built with a road infrastructure exchange component and a priority validator that performs basic checks on priority requests coming from emergency vehicles. The responsibility to grant these requests (taking current road conditions into account) lies with the ITSApp component of the intelligent traffic controller (Imec, 2022).

The intelligent traffic light systems in Belgium employ a long-range component, enabling emergency vehicles to send messages to the traffic light five minutes in advance. In contrast, the ITS G5 short-range system only allows communication within approximately 100 meters before reaching the traffic light. Priority requests (SRM messages) sent by mobility applications through the road infrastructure exchange to an intelligent traffic light controller are redirected to the traffic light priority validator for validation. The request is passed on when it does not conflict with the priority rules and is technically validated. An invalid request (the denial message SSM) is sent via the interchange to the original mobility application. The traffic light priority monitor ensures the technical functionality of the priority request information stream. Latency checks are performed on incoming and outgoing priority messages (SRM and SSM), and the number of rejections is evaluated (*Mobilidata*, 2022).

The PRG (priority request generator) determines that the emergency vehicle passes the intersection's stop line and requests an SRM (priority cancellation). The controller removes the request, allowing the traffic controller to resume the typical operational sequence.

Emergency vehicles must be equipped with an application or built-in information system capable of requesting priority. This system can be an app or an on-board unit (Imec, 2022).

When multiple intersections are situated in close proximity, they can communicate and coordinate with one another to optimize traffic flow. This interconnected system allows emergency vehicles to experience a smoother transit, ensuring that as they approach each intersection, the traffic signals prioritize their passage by granting a green phase when traffic conditions allow it (*Mobilidata*, 2022).

Talking Traffic, a program for central communication from the Netherlands, focuses on collaboration to develop solutions for increasingly congested traffic, with an implementation for long-range C-ITS. Part of this program focuses on absolute prioritization for emergency vehicles, meaning that traffic lights will turn green for the road segment where the emergency vehicle is located. The talking traffic system technology functions similarly to the intelligent traffic lights system in Belgium, utilizing long-range C-ITS technology. The systems employ a cloud service to monitor the GPS data of an emergency vehicle, the cloud service can detect when an emergency vehicle is approaching an intersection and generates a signal request message (SRM). A response signal status message (SSM) is returned to the emergency vehicle and the traffic controller (*Mobilidata,* 2022).

4. RESEARCH LOCATION

This study conducts simulations of an intersection in Leuven, called Tiensepoort, to evaluate the impact of intelligent traffic light systems on emergency travel times.

Leuven is centrally located in Belgium within the province of Flemish Brabant. Situated near major cities in Belgium, Leuven has a central location. Antwerp, Brussels, and Hasselt are among the cities surrounding Leuven. Antwerp lies approximately 55 kilometers away, Brussels is 30 kilometers from Leuven, and Hasselt is 60 kilometers away. With an area of 56,63 square kilometers, Leuven is one of the 13 central cities in Belgium. Despite its relatively small size, Leuven has a population of 103,802, resulting in a high population density of 2,5521 individuals per square kilometer. Over the last few years, Leuven has experienced significant population growth, and there are clear indicators that this trend will continue. The population of Leuven has been increasing by approximately 1% annually, surpassing the average growth rate of Flanders and other central cities of Belgium. The population numbers of Leuven do not encompass the student population of the University and colleges of Leuven, making the population numbers underestimated. Approximately 42,000 students live in dormitories, further contributing to the city's community. The UZ Leuven Gasthuisberg is a university hospital located in Leuven, Belgium. It is the largest hospital in Belgium and the only university hospital in Flemish Brabant.

The hospital is affiliated with the Catholic University of Leuven and plays a significant role in research, education, and patient care. Leuven's fire station is located next to the hospital. The fire station in Leuven is part of the East Emergency Response Zone in Flemish Brabant, and the police services have multiple locations within Leuven (*Brandweerpost Leuven - Hulpverleningszone Oost Vlaams-Brabant*, n.d.).

The R32-ring road in Leuven, with seven intersections regulated by traffic lights, provides a unique case for studying intelligent traffic light implementation.

5. APPLICATIONS OF ITLC: CASE STUDIES

A study of Talking Traffic by BeMobile indicates a percentage speed increase of road inspectors just before an intersection (-100 to 0m) with iTLC, ranging from 10% to 46% with an average of 30%. The percentage represents the average speed difference for road inspectors who request absolute priority. The speed difference is the percentage difference between intersection crossings in the baseline measurement (0-measurement) and the follow-up measurement (1-measurement). Meaning that extending absolute priority results in no intersection crossing at a lower speed.

The study shows that the travel time of road inspectors decreases by 15%, and the average number of stops reduces by 71% when absolute priority is applied to a road segment with nine iTLC. The study analyzed travel time over the baseline and follow-up measurement, revealing travel time variability decreases, leading to the conclusion that absolute prioritization enhances the reliability of travel times for priority vehicles (BeMobile, 2021).

TABLE 1 Travel time emergency vehicles (BeMobile, 2021)

Metric	Result
Speed increase before intersection	10% – 46% (avg. 30%)
Travel time reduction	15%
Reduction in number of stops	71%
Travel time variability	Decreased
Reliability	Improved

A study by Umovity, encompassing over 900 intersections, demonstrates that applying emergency priority protocols enables emergency responders to arrive at the scene an average of 22 seconds faster (PTV Webinar, 2024).

Applied Information Inc., based in Georgia, USA, has developed an emergency vehicle preemption system that prioritizes emergency vehicles at intersections. This system enhances safety by halting other vehicles and preventing crashes while reducing travel times by up to 20%. According to the company's research, this system saves emergency vehicles an average of 11 seconds per traffic light (Applied Information Inc., 2025).

TABLE 2 Travel time emergency vehicles (PTV Webinar, 2024) and Applied Information Inc., 2025)

Metric	Result
Average reduction in travel time	22 seconds
Travel time saved per traffic light	11 seconds
Overall reduction in response time	Up to 20%
Safety impact	Fewer crashes at junctions

A 2025 study by Mobilidata examined the deployment of intelligent traffic lights in Ghent, Belgium, focusing on the frequency with which emergency vehicles were granted green light priority at intersections. The study analyzed emergency vehicles equipped with fully functional priority request software as they passed the first four iTLC-controlled traffic signals during observation. Notably, these four traffic lights collectively managed eight intersections, with some systems controlling multiple closely located intersections.

To evaluate the effectiveness of priority signaling, researchers utilized log data from the traffic lights to determine whether emergency vehicles encountered green or red signals upon the intersection approach. The findings indicate that, at nearly all intersections, emergency vehicles could pass through on a green light. However, one intersection experienced a technical issue that resulted in slightly reduced performance compared to the others.

To ensure a comprehensive analysis, both absolute counts of recorded passages is used to assess statistical relevance and percentage distributions. The results for each intersection are shown in Table 3. With an average green phase priority of 97,76%, excluding the fifth intersection (Vandenberghe, 2025).

TABLE 3 Green light priority (Vandenberghe, 2025)

Metric	1	2	3	4	5*	6	7	8	Average
% green	97.3	100.0	96.7	93.2	82.9	100.0	97.1	100.0	97.76
% red	2.7	0.0	3.3	6.8	17.1	0.0	2.9	0.0	2.24

**Intersection 5 was excluded from the average calculation*

6. INSTRUMENTS AND DATA COLLECTION

The microsimulation model was developed using real traffic data obtained from road traffic monitoring systems. Measurement induction loops are used by Agentschap Wegen en Verkeer to obtain intersection traffic volumes during peak hours. These data were used as input for the simulation model.

The microscopic simulation software PTV Vissim version 2023, designed for multimodal traffic simulation, was used to reproduce the traffic patterns of all vehicles on a microscopic level. The car-following model allows for scientifically based simulation of vehicle dynamics, making evaluating and optimizing the model's performance possible. The model was calibrated and validated to ensure the simulation conditions accurately reflect real-world traffic conditions (Traffic Simulation Software | PTV Vissim n.d.).

The baseline measurement (0) represents the simulation environment without any modifications (smart traffic lights), while the follow-up measurement (1) includes intelligent traffic light controllers. Both simulations are based on multiple parameters:

- The geometry of the intersection and the overall network: This includes background images, links and connectors, number of lanes, and speed limits. These elements are essential to replicate the physical layout of the intersection as accurately as possible in the simulation.

- Traffic demand and routing: Traffic volumes during peak hours were used as input. Routing is defined for general traffic and emergency vehicles to reflect realistic traffic flows.
- Signal control and conflicts: Signal v-plans were used to obtain information about the signal controllers. Signal controllers were implemented for the baseline measurement (smart traffic lights) and the follow-up measurement (intelligent traffic lights).
- Several routing approaches are evaluated based on travel time and queue lengths. In each scenario, the emergency vehicle consistently enters the network from the same approach road but proceeds toward a different destination road (right, forward, and left). This variation is crucial because each maneuver interacts differently with the signal phases and creates distinct conflict points. Analyzing all three scenarios, the study captures a complete picture of how emergency vehicle priority affects queue lengths and overall intersection performance. This approach strengthens the validity and applicability of the results in real-world traffic conditions.
- Speed consideration emergency vehicle: The degree to which emergency vehicles exceed speed limits is influenced by several factors, including road conditions and traffic density. A study conducted in Finland analyzed ambulance speed during urgent missions. This resulted in surpassing the speed limit by 17.6km/h on a 50km/h speed limit. For this study, a 60 km/h speed was assumed for emergency vehicles, acknowledging that the extent to which they exceed speed limits varies significantly depending on the road type (Pappinen & Nordquist, 2022).
- Pedestrians and cyclist are not simulated into the model. However, the signal timing of pedestrians and cyclists are incorporated into the model.

Figure 1 shows the model-building framework in PTV Vissim 2023.

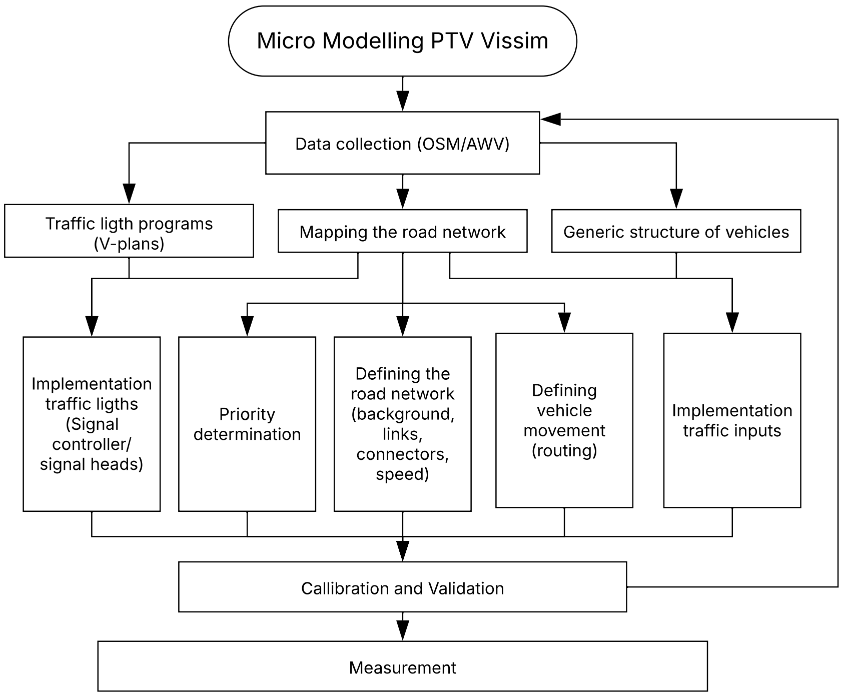


FIGURE 1 Model framework PTV Vissim 2023

The simulation's smart and intelligent traffic lights were created using VISVAP and a PUA (Program user application) file. This was necessary to allow for dynamic signal control. In Vissim, both simulation models operate based on virtual detectors (loops), although, in real-life conditions, only the smart traffic lights use inductive loops. Intelligent traffic lights, in reality, rely on cloud-based communication systems to detect and prioritize emergency vehicles. However, this type of detection cannot be directly implemented in Vissim. Instead, detectors were used to simulate the same functional effect. These virtual detectors were programmed to detect only emergency vehicles and to activate priority logic when an emergency vehicle approaches.

7. RESULTS

7.1. Travel time

The implementation of signal preemption significantly reduces the travel time for emergency vehicles approaching the intersection via the Geldenaaksesteenweg. For right-turning, left-turning, and forward movement, the average travel time decreased by 27.88 seconds, corresponding to a 37.01% reduction. This consistent improvement across all directions confirms the effectiveness of signal prioritization in reducing travel time for emergency vehicles.

Simulation results further show that vehicles traveling in the same direction as the prioritized emergency vehicle experience negligible changes in travel time, suggesting that the adjusted signal phases accommodate emergency vehicle access without substantially disrupting codirectional traffic flow.

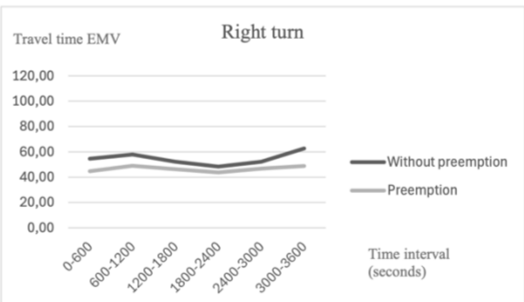
In contrast, opposing or conflicting approaches, which receive reduced green signal time due to the activation of signal preemption, exhibit varying degrees of delay. The observed increase in travel time ranges from 1.14 seconds up to 47.56 seconds, translating to a relative rise between 1.64% and 19.33%, depending on the specific intersection road.

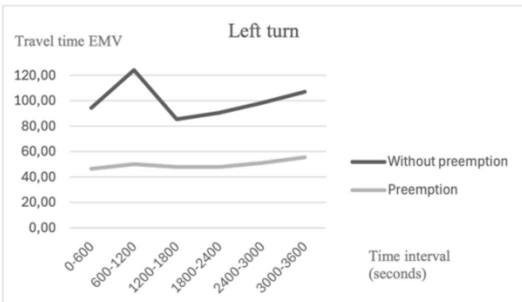
An average increase in travel time of 8.84 seconds (7.53%) was observed across all intersection roads, excluding the prioritized road used by the emergency vehicle.

The Tiensestraat exhibits the most significant negative impact, this is the approach entering the intersection from the city center of Leuven.

Turning right at the Tiensestraat results in the highest increase in travel time, with an average delay of 47.56 seconds. This can be attributed to the design of the intersection, which may hinder the efficient flow of right-turning vehicles, indicating a clear spillover effect resulting from interrupted signal phases.

Without signal preemption, emergency vehicle travel times exhibit high sensitivity to signal cycle timings and traffic conditions, resulting in substantial variability across different time intervals. This is reflected in the fluctuating travel time curves in Figure 2. Conversely, signal preemption facilitates a more regulated and consistent passage through the intersection, as evidenced by the relatively straight and uniform lines in Figure 2.





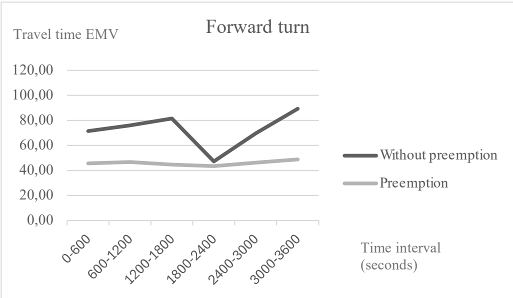


FIGURE 2 Travel time emergency vehicles with and without priority

TABLE 4 Impact of signal preemption on travel time

Direction	**Avg. travel time without preemption (s)**	**Avg. travel time with preemption (s)**	**Difference (s)**	**change (%)**
Average				
Emergency vehicle	75.33	47.45	- 27.88	- 37.01
Geldenaaksevest → Tiensevest	71.66	71.42	- 0.24	- 0.34
Geldenaaksevest → Tiensesteenweg	53.51	54.16	+ 0.65	+ 1.19
Geldenaaksevest → Blijde Inkomststraat	109.63	107.96	- 1.67	- 1.54
Tiensestraat → Tiensesteenweg	95.48	97.95	+ 2.47	+ 2.52
Tiensestraat → Geldenaaksevest	198.52	246.08	+ 47.56	+ 19.33
Tiensestraat → Tiensevest	90.13	94.97	+ 4.84	+ 5.10
Tiensesteenweg → Blijde Inkomststraat	69.01	83.83	+ 14.82	+ 17.68
Tiensesteenweg → Tiensevest	73.73	89.01	+ 15.28	+ 17.16
Tiensesteenweg → Geldenaaksevest	73.92	90.51	+ 16.59	+ 18.33
Tiensevest → Blijde Inkomststraat	37.09	39.18	+ 1.57	+ 5.65
Tiensevest → Geldenaaksevest	69.82	70.96	+ 1.14	+ 1.64
Tiensevest → Tiensesteenweg	88.48	91.58	+ 3.10	+3.67

7.2. Queue length

This section presents the effects of implementing emergency vehicle signal priority on the queue lengths of all intersection roads.

The road on which the emergency vehicle enters the intersection (Geldenaaksevest) shows a slight overall reduction in average queue length across all simulated directions (right, straight, and left), with a decrease of 2.12%, equivalent to 1.27 meters. This supports the effectiveness of signal preemption in facilitating emergency vehicle passage and reducing delays on its path.

The most significant increased queue length is observed on the Tiensestraat, which is the direction approaching the intersection from the city of Leuven, with an increased queue length average of 18.17 meters, corresponding to a 26.18% increase. This indicates a clear adverse spillover effect due to interrupted or shortened green phases caused by emergency vehicle prioritization.

To avoid biased results, the average impact on general traffic was assessed while excluding data from the road on which the emergency vehicle approaches the intersection. Across the non-prioritized roads, average queue lengths increase by 13.44 meters or 13.26%. This rise reflects the delays induced by non-prioritized approaches when signal preemption is activated, forcing them to remain at red longer than usual as shown in Figure 3.

These results highlight the operational trade-off between emergency response preemption and overall traffic performance. While signal preemption effectively clears the way for emergency vehicles, it introduces measurable delays and localized congestion for other road users.

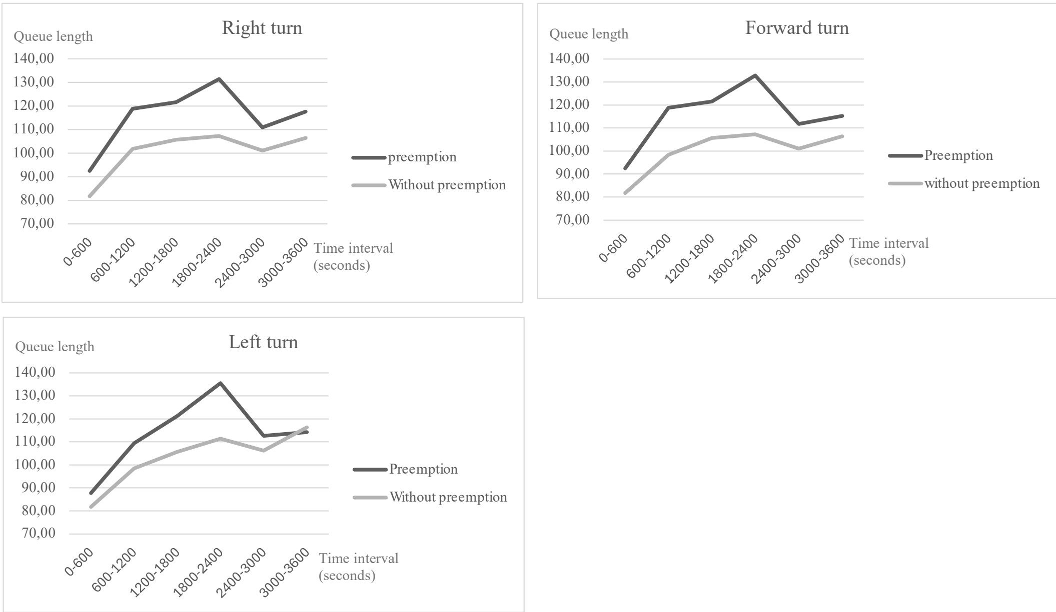


FIGURE 3 Queue length with and without preemption on non-prioritized intersection roads

TABLE 5 Average queue lengths per intersection road

Road at the intersection	Avg. queue length without priority (m)	Avg. queue length with priority (m)	Difference (m)	change (%)
Right turn				
Prioritized road	58.73	57.37	- 1.36	- 2.3
Tiensesteenweg	145.90	169.02	+ 23.90	+ 16.5
Tiensevest	87.93	89.64	+ 1.71	+ 2
Tiensestraat	68.96	87.76	+ 18.80	+ 27.26
Average (all)	90.18	102.10	+ 10. 76	+ 11.9
Average non-prioritized roads	**100.67**	**115.47**	**+ 14.80**	**+ 14.71**
Forward				
Prioritized road	59.95	58.19	- 1.76	- 2.94
Tiensesteenweg	144	167.12	+ 23.12	+ 16.06
Tiensevest	87.33	91.66	+ 4.33	+ 4.95
Tiensestraat	68.96	87.53	+ 18.57	+ 26.93
Average (all)	90.06	101.12	+ 11.06	+ 12.29
Average non-prioritized roads	**100.10**	**115.44**	**+ 15.34**	**+ 15.33**
Left turn				
Prioritized road	60.74	60.04	- 0.70	- 1.16
Tiensesteenweg	150.48	162.35	+ 11.86	+ 7.88

Tiensevest	88.92	90.40	+ 1.48	+ 1.67
Tiensestraat	70.45	87.60	+ 17.16	+ 24.35
Average (all)	92.65	100.10	+ 7.45	+ 8.04
Average non-prioritized roads	**103.28**	**113.45**	**+ 10.17**	**+ 9.84**
Average of all directions (right, forward and left)				
Prioritized road	59.80	58.53	- 1.27	- 2.12
Non-prioritized roads (3)	**101.35**	**114.79**	**+ 13.44**	**+ 13.26**

**Prioritized road: Geldenaaksevest (R32)*

**Non-prioritized roads: Tiensesteenweg, Tiensevest and Tiensestraat*

8. DISCUSSION

Previous studies have demonstrated that implementing green phase preemption at signalized intersections significantly reduces average travel times for emergency vehicles.

The results of this study corroborate these findings, showing that green phase preemption at an intelligent traffic signal reduces emergency vehicle travel time by up to 27.88 seconds, representing a 37.01% decrease at the studied intersection.

However, a spillover effect is observed on other traffic movements at the intersection, as the green phase preemption for emergency vehicles leads to increased travel times and queue lengths for conflicting traffic streams.

However, it is important to note that the microsimulation incorporated pedestrian and cyclist signal timing without fully modeling their actual behavior, potentially leading to overestimating the benefits. Future research should integrate detailed pedestrian and cyclist interactions to improve accuracy.

Furthermore, the effectiveness of signal preemption diminishes with increasing travel distance, as emergency vehicles face multiple signals, conflicting traffic flows, and other delays. This limitation has been recognized in earlier analyses (Hunt et al., 1995) and should be considered when generalizing these results.

Belgian intelligent traffic lights utilize long-range communication, allowing emergency vehicles to request priority up to five minutes in advance. In contrast, the ITS-G5 short-range system is limited to approximately 100 meters. For this simulation, a minimum green phase of five seconds for motorized traffic and a 15-second pedestrian clearance time necessitates emergency vehicles sending priority requests at least 20 seconds before arrival. At 60 km/h (16.67 m/s), this corresponds to a minimum notification distance of 333 meters.

This highlights the critical importance of long-range communication in ensuring timely priority activation. Short-range systems would fail to provide adequate lead time, compromising emergency response efficiency and traffic signal preemption effectiveness.

While the developed simulation model can potentially be applied to other cities, it is important to acknowledge the challenges in generalizing the model. Although the model provides valuable insights and recommendations, it must be approached cautiously when considering its applicability to other cities.

Each city and intersection have unique characteristics, including infrastructure, signal times, and traffic patterns. Therefore, while the model serves as a valuable starting point, it is essential to recognize the need for customization and adaptation to suit the specific context of each city and intersection.

By recognizing the limitations of generalization, city authorities, and stakeholders can approach the model as a valuable reference, using it as a foundation for further research and adaptations of other cities.

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Appendix

TABLE 6 Definition of words used in the paper

Word	Source	Definition
Travel time	(Oliveira & Duarte, n.d.)	The time required to travel from the starting point of the emergency vehicles to the location of an emergency event.
Green phase preemption	(U.S. Department of Transportation, n.d.)	Giving emergency vehicles the right of way at and trough a signal. The right of way is achieved with a green indication on the approach of the vehicle requestion preemption.
Boolean logic	(Harding, 2025)	A system of logic where values are either true or false, often represented as 1 or 0

Long-range	(Australian Government, 2022)	Long-range cooperative intelligent transport systems utilize cellular networks (like 4G, 5G) to enable communication between traffic infrastructure and vehicles.
C-ITS	(Be-Mobile, 2025)	Cooperative intelligent transport systems allows vehicles to communicate with the traffic infrastructure, including traffic lights, to improve traffic flow and safety
iTLC	(Crow, 2023)	An intelligent traffic light controller is a system that uses technology and algorithms to optimize traffic flow at intersections
TLC	(Mobilidata, 2022)	Executes the actual traffic light signal changes at the intersection
ITSApp	(Mobilidata, 2022)	Translates traffic control decisions into messages for connected emergency vehicles and vice versa. Interfaces directly with both TLC and RIS.
RIS	(Mobilidata, 2022)	The reconfigurable intelligent surface is responsible for maintaining a local dynamic map of the junction, handling C-ITS messages for the junction, and network security to the outside world.
MI-interface	(Mobilidata, 2022)	The Mobilidata Interface is a standardized communication protocol used within the Mobilidata ecosystem in Belgium to facilitate real-time data exchange between intelligent traffic lights and other components of the C-ITS
AMQP protocol	(Selvam, 2024)	The advanced message queuing protocol is a widely used open standard for messaging, enabling asynchronous communication between applications and systems
GDPR-compliant	(Wolford, 2024)	GDPR compliance refers to adhering to the general data protection regulation, a set of rules established by the European Union to protect individuals' personal data and privacy
SRM messages	(Mobilidata, 2022)	Signal request messages are standardized digital messages transmitted by authorized vehicles (emergency services) to request priority at upcoming intersections.
SSM messages	(Mobilidata, 2022)	Signal status message, a standardized digital message that communicates the status of a previously sent SRM from the intersection to the

		emergency vehicle. Whether the request is received and the action taken (accepted, denied, delayed)
Spillover effect	(Romo et al., 2024)	A spillover effect in traffic management means that changes or interventions on one road or traffic stream cause unintended consequences on nearby roads or traffic flows.
Operational trade-off	(Akbar et al., 2020)	An operational trade-off means balancing two conflicting objectives where improving one aspect leads to a compromise or negative impact on another

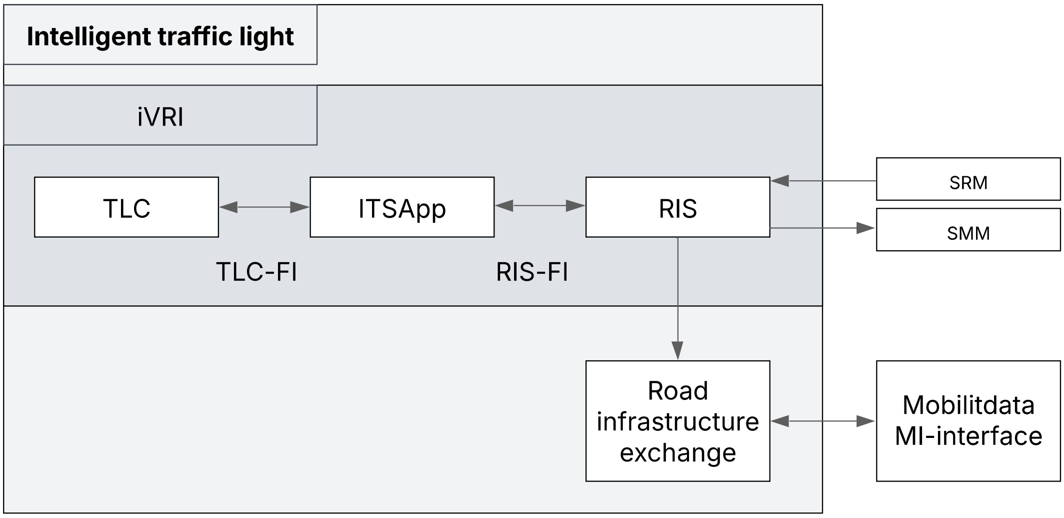

Fig. 4. Simplified architecture iVRI, Belgium