ADAPTIVE TRAFFIC SIGNAL CONTROL FOR ENHANCED SAFETY AND EFFICIENCY AT ROAD INTERSECTIONS NEAR RAILWAY

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Resume
In this study is proposed and evaluated an adaptive traffic signal control system designed to synchronize the road and railway signaling, minimize collision risks, and improve traffic flow. Results show that adaptive control reduced average queue length for over 46%, cut vehicle delay for 34%, lowered stop frequency for 74%, and decreased CO2 emissions for nearly 46% compared to static control. Further analysis examined the effect of varying the distance between intersections and railway crossings, revealing significant safety and efficiency gains when the separation exceeded 80 m. The findings demonstrate that intelligent, sensor driven traffic management can substantially enhance both safety and throughput in these complex transport nodes, while delivering environmental benefits.

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1 Introduction

Railway crossings, and indeed any at-grade intersections of roads with rail lines, represent particularly high-risk locations in terms of road traffic safety. Accidents at these crossings often have fatal consequences due to the specific characteristics of rail vehicles, such as their inability to perform evasive maneuvers, immense mass, and extended braking distances (for example, a passenger train weighing approximately 1000 tons requires a braking distance of around 1000 meters when traveling at 100 km/h). Although the absolute number of these accidents may be relatively low, their severity is significant. Accidents at railway crossings can significantly disrupt the train operations and create ripple effects throughout the entire transport system.

Managing a road intersection in the vicinity of a railway crossing is a complex task that demands careful consideration of multiple factors to ensure both safety and traffic flow. Designing the control logic for such an intersection requires a thorough evaluation of various elements, with the primary objective being to minimize risks and guarantee a smooth flow of traffic. Among the existing problems, the following should be highlighted:

a) Collisions are the most significant problem, involving impacts between trains and vehicles, as well as between trains and pedestrians. Given the proximity of a railway crossing to a road intersection, improper management can lead to extremely hazardous situations where vehicles accumulate directly on or near the crossing during a train's passage.
b) Delays are another critical issue. The formation of long queues at the road intersection due to the closure of the railway crossing can cause significant delays and complications in the overall traffic flow. It is crucial to find a delicate balance between ensuring safety and maintaining traffic fluidity.
c) Complex Control presents a significant challenge. The control logic for an intersection with an adjacent railway crossing must be highly intricate

and exceptionally reliable. It must account for a variety of factors, including train frequency, road traffic intensity, duration of crossing closure, and other dynamic variables.

d) Pedestrian and Cyclist Safety is also a critical concern. An intersection with a railway crossing inherently poses an elevated risk to pedestrians and cyclists. It is crucial to ensure their safety through the use of adequate signage, adequate lighting, and, where appropriate, physical barriers.
e) Designing the control logic for an intersection with a railway crossing is a complex process that demands collaboration among specialists in various fields. This collaboration includes the traffic engineers, railway designers, and representatives of the local government.

This study's focus was specifically on addressing the last problem mentioned. The ideal solution is the complete separation of the road and rail traffic, for example, by building an overpass or underpass. Although such a solution would eliminate collision risks and ensure smooth traffic flow, it is not always feasible, primarily due to financial and sometimes spatial constraints.

In the cases where the complete separation is not possible, it becomes crucial to ensure precise coordination between the traffic and railway signaling systems. This coordination involves synchronizing the road traffic signalization (TSD, Traffic Signal Device) and the level crossing protection device (LCI, Level Crossing Installation). The activation of the LCI should automatically influence the road traffic signals, preventing vehicles from entering the crossing during a train's passage.

Adequate sight distances and the strategic placement of warning devices contribute significantly to the safety of the solution; sufficient visibility is crucial for drivers to perceive warning signals promptly. Warning devices, such as flashing lights and barriers, must be installed following applicable standards and regulations. For the TSD, an adaptive control type must be employed. This control allows the signal plan to change in response to the LCI entering a warning state. An example of such a control approach is a dynamic TSD, which, when implemented, enables signal plans to adjust to the current traffic situation. This control utilizes detectors to monitor traffic intensity and make subsequent adjustments to the duration of the green and red phases for individual directions.

1.1 Literature review

Several publications have addressed specific traffic control scenarios where a rail intersects the urban road. The right-of-way conflict usually favors the train for technical reasons, such as its long brake times and carriage lengths [1]. In reference [2] was addressed a specific configuration of a T-shaped road intersection with a nearby railway crossing. This arrangement very often introduces additional risks arising from the phenomenon known as "back-blocking," i.e., the blocking of road vehicles located on the railway crossing when a train approaches and passes through it (a specific type of spillback). From the perspective of managing a nearby intersection, both static and dynamic control algorithms are available [3]. Authors of [4] examined the technical and safety aspects of the issue, with an emphasis on the so-called preemption systems for road signals. It provides information on practices related to traffic signal preemption, maintenance, funding, and operations in both the United States and Canada. In studies [1, 5-7] were analyzed the specific control strategies, referred to, for example, as the TPS-DT algorithm (Transition Preemption Strategy Dual Track) or the ITPS algorithm (Improved Transition Preemption Strategy). A control strategy known as CAPRI (Categorized Arrivals-Based Phase Re-optimization at Intersections), which integrates transit signal priority and rail/emergency preemption within a dynamic programming-based real-time traffic adaptive signal control system, was introduced in [8]. A brief comparison of the last-mentioned strategies is available in Table 1.

The research presented in [9] highlights the impact of various intelligent transportation systems (in-vehicle video, in-vehicle audio, flashing signals on the roadway) using an advanced driving simulator (VISSIM 5.4) on driver behavior when crossing railway level crossings (LCs).

The analysis of sources cited, as well as of others in the literature, reveals that simulation models are frequently used to evaluate the effectiveness of various intersection dynamic control strategies. These models can be used to analyze traffic flow and identify potential problems. Furthermore, simulations also incorporate various safety analyses, which are crucial for identifying risk factors and designing measures to minimize the risk of accidents [10].

Optimization of traffic processes is also a key consideration [11]. In the future, new safety technologies

Table 1 *Brief comparison of dynamic control algorithms*

TPS-DT	CAPRI	ITPS
Extended strategy for dual track LCs	Adaptive control based on vehicle categorization	Improved version of TPS-DT with advanced adaptation
Safe release of the LC, second train detection, pedestrian protection	Real-time traffic monitoring, dynamic phase optimization	Predictive models, sensor data, fewer repetitive changes
Reduced increased blockage, safety, smoother traffic flow	Priority vehicles, for key reduced delays, effective intersection utilization	Congestion minimization, enhanced safety, smoother passage

in connected and autonomous vehicles could help address the problem discussed [12]. Connected vehicle technology has the potential to significantly enhance the safety of railway crossings by enabling communication between vehicles and the infrastructure and exchanging information. When designing and implementing the solutions considered, the country's applicable legislation also plays a role. This legislation includes laws, technical standards, and technical and organizational regulations that specify traffic rules, principles for the placement of traffic signs and devices, as well as procedures for the construction and maintenance of road and rail infrastructure. For the specific case considered here, the relevant legal framework consists of legislative documents [13-17].

1.2 Motivation

The intersection of roads in the vicinity of a railway crossing presents a specific challenge because it coordinates two types of traffic, each with distinct dynamic characteristics and rules. The LCs represent not only the physical intersection of railway track and a road but also an intersection of responsibilities and interests [18]. When a train crosses the railway crossing, it is essential to stop the road traffic. Incorrect signal timing can cause vehicles to get stuck on the tracks, significantly increasing the risk of collisions. The simulation tool used defines a collision as an event in which the simulation detects that two vehicles occupy the same physical space, i.e., their rectangular vehicle envelopes overlap. This is not a dynamic crash model (no forces, deformation, or injury simulation). It is simply a violation of minimum separation that the model could not prevent. In addition, the direction of road traffic and railway signaling must be coordinated. If there is a lack of effective communication between the railway and road control systems, the situation could be misjudged, further escalating the risk of accidents. There are several reasons why this problem needs to be addressed. The primary reason for this is safety. For example, in 2023, Slovakia had approximately 2,065 railway crossings along its 3,630 km-long railway networks, with almost half lacking lights or barriers, which significantly increases the risk of accidents. These locations were responsible for thirty-four accidents recorded in 2023, resulting in 11 fatalities. According to annual EU statistics, Slovakia's average fatal railway accident rate is four times higher than the rate in the European Union. Key contributing factors include driver inattention, inadequate infrastructure, and insufficient safety provisions. Consequently, modernizing railway crossings and implementing enhanced safety measures are imperative. Another reason is to ensure traffic flow. Intersections near railway crossings that are not properly synchronized can cause traffic congestion. The constant stopping of vehicles at the crossing reduces traffic efficiency and increases the risk of accidents. An integrated control system that coordinates traffic signals with train movements can reduce waiting times and increase traffic handling capacity. The third reason covers economic and environmental impacts. Effective management of intersections and crossings can reduce fuel consumption and CO_2 emissions, resulting in improved air quality, and reduce repair costs after accidents while promoting a more sustainable and resilient transport infrastructure. Thus, the following safety methodology was used: safety performance was evaluated using conflict-based indicators extracted directly from the simulation environment. A safety critical event was registered when the two vehicle envelopes overlap. To assess the interaction between the intersection and the railway crossing, the authors' intention was to monitor the following indicators: *vehicle–train conflicts* - road vehicles present in the conflict zone during active LCI warning or barrier descent; *blocked crossing events* - vehicles stopped on the crossing or its clearance zone, indicating potential entrapment; *crossing clearance time* - time needed to evacuate the zone after LCI activation; *queue spillback* - queues extending toward the crossing and reducing the safety buffer. All indicators were obtained from simulation logs and verified through visual inspection.

2 Proposed solution concept

The objective of this solution is to develop an effective traffic signal coordination system to ensure optimal intersection performance in various traffic scenarios. The proposed solution includes the following components: *Traffic situation detection* - use of sensors to identify vehicles, pedestrians, and approaching trains; *Traffic Signal Synchronization* - implementation of adaptive algorithms to dynamically adjust traffic signals based on current conditions; *Simulation and testing* - verification of the proposed system using advanced simulation tools to analyze traffic flow and optimize control parameters; *Safety Mechanisms* - introduction of measures to prevent hazardous situations, such as blockade of the railway crossing by vehicles or signal failure.

The intersection control near a railway crossing can be categorized into three basic modes of operation: standard mode, approaching train detection mode, and emergency mode. The standard mode reflects the typical operation of the intersection without any intervention from the LCI. The approaching train detection mode activates when a rail vehicle approaches, adjusting the signal timing cycles to ensure safe clearance of the LC area. The emergency mode, as a specific control category, is used in extraordinary situations, such as traffic accidents, signaling equipment failures, or vehicles trapped on the crossing. This mode requires prompt and measures coordinated to ensure maximum safety for all road users.

2.1 Standard mode

In the standard mode, the intersection operates in a standard manner based on preset signal plans, which ensure the smooth and safe movement of vehicles and pedestrians. Traffic signals control traffic according to fixed time intervals or dynamically, depending on the current traffic situation. This mode is applied in normal circumstances, when no immediate threat is detected from an approaching train or other emergency. The intersection operates efficiently, demonstrating a strong commitment to traffic regulations and ensuring clear pathways for all vehicles to follow. In this mode, the traffic signal control at the intersection is not influenced by railway traffic. The signal phases are configured to maximize the traffic flow and are fixed or continuously adjusted based on sensor data in the case of adaptive control. With adaptive control, the duration of individual phases changes dynamically in response to the traffic intensity on each intersection arm. Furthermore, within the normal mode, emphasis is placed on prioritizing primary traffic directions. This prioritization ensures greater throughput for the busiest lanes. In static control, this is achieved through predefined time intervals. In contrast, adaptive control flexibly adjusts signal phase duration based on current traffic data, thereby minimizing delays and preventing queue formation. The individual components of the traffic system operate independently and under pre-established rules. However, if an approaching train is detected, the situation changes, and the intersection switches to a special control mode that ensures the safety of all the road users.

2.2 Approaching train detection mode

When a train approaches a railway crossing, the intersection activates a safety mode, providing a secure passage that significantly reduces the chances of traffic accidents and congestion. This mode is triggered automatically based on signals from detection sensors strategically placed at a distance that allows the timely identification of the train and the implementation of adequate measures. The system first detects the approaching train via sensors or other monitoring technologies, which initiates a process of gradually clearing the track area. To prevent vehicles from getting stuck on the tracks just before a train arrives, the green signals for vehicles approaching the crossing are deactivated. If vehicles are already at the crossing, the system gives them priority to pass safely. The green signal may be extended dynamically if necessary. Once the track area is clear, the intersection controller activates a red phase on all approaches to the crossing, preventing more vehicles from entering. At the LC, the warning lights are on and sound alerts indicate the approaching train while barrier systems descend simultaneously. This phase is precisely timed to prevent premature closure of the crossing before the area is cleared. In the event of high traffic volume, such as during rush hour, the control system can dynamically adjust the phase duration based on the current situation, ensuring smooth and safe traffic coordination. Intelligent algorithms enable the real-time analysis of traffic intensity, optimizing the signaling process.

2.3 Emergency mode

The LCI system enters emergency mode in response to unexpected situations that could jeopardize the safety of road and rail traffic. Such situations include traffic signal failures, trapped vehicles at railway crossings, traffic accidents, LCI failures, or other unexpected events. The primary objective of this mode is to minimize the risk of collision and ensure an effective and coordinated response to the emerging situation. Upon detecting an obstacle in the crossing area, such as a trapped vehicle, a pedestrian, or a fallen object, modern monitoring systems (including sensors and cameras equipped with radar or thermal imaging technology) immediately activate a warning protocol. This technology enables the precise identification and classification of obstacle types, thus minimizing false alarms. The system then automatically switches the traffic signals to emergency mode, where, for instance, all signals begin to flash red. This mode stops the traffic in all directions, preventing additional vehicles from entering the risk zone. At the same time, this mode signals the increased need for caution among drivers. If the problem is severe, the system immediately informs the railway dispatch, which can issue a command to stop or reduce the speed of a train before it reaches the crossing. Prompt communication between road and rail infrastructure is crucial to avoid serious accidents. Upon detecting a trapped obstacle, the system dynamically adjusts the signal plan of the intersection to allow safe removal of potentially trapped vehicles. This plan may include extending the green phase of traffic flow away from the crossing or preventing other vehicles from accessing the critical zone. These changes are executed in real time, based on data from traffic sensors and algorithms. In the event of an LCI failure, a backup traffic control method is activated, which may involve manual traffic management by police or railway personnel. In critical situations, the intersection might be temporarily closed to prevent an uncontrolled situation. The emergency mode remains active until the problem is resolved. Once the obstacle is removed, the signaling and safety systems are restored, and the current traffic situation is analyzed, the intersection gradually returns to standard control mode. This process modifies signal plans to reduce traffic delays. Only when all the safety criteria are met does the intersection resume regular operation.

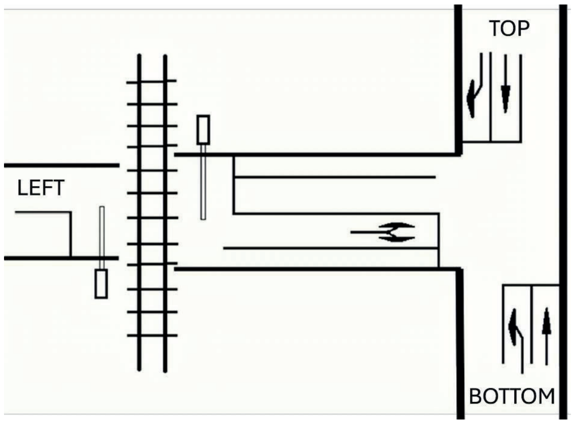

Figure 1 *Schematic layout of the intersection and crossing*

3 Results and discussion

Considering various simulation tools and the specific requirements that result from the nature of the problems, authors have decided to use PTV VISSIM [19] as the primary tool for traffic simulation, as it models detailed traffic flows and the behavior of individual road users. In model implementation, a road network and lanes were created (corresponding to the situation in Figure 1), defined the railway track and conflict zone, positioned signals, configured basic settings, created logical signal plans, synchronized railway and road signaling, and integrated road traffic and train detectors.

3.1 Simulation setup and input parameters

The parameters were selected to reflect the typical operating conditions of an urban intersection located in close proximity to a railway level crossing. Traffic volumes were assigned to each approach based on a representative distribution of flows on a minor road intersecting a main road. The total traffic demand was set at 900 vehicles/hour, with the following proportional distribution: 80% for main road (40% for TOP, 40% for BOTTOM), and 20% for side approach (from LEFT). Vehicle composition consisted of 92% passenger cars, 6% light commercial vehicles, and 2% heavy vehicles, following standard urban traffic profiles. Train arrivals were modeled as periodic events with a headway of 10 minutes, corresponding to a frequency of 6 trains per hour. Two train detectors were implemented - an approach detector positioned 350 m before the level crossing, triggering the pre-emption logic, and an exit detector positioned 50 m beyond the crossing, confirming train clearance. The level crossing protection system (LCI) activation time was set to 6 seconds for warning lights and 8 seconds for barrier descent. Each scenario (static vs. adaptive control) was simulated for a simulation horizon of 3600 seconds. To reduce stochastic variability, 10 independent replications were performed per scenario, and all performance indicators were averaged across runs. Vehicle detectors were placed approximately 20–25 m upstream of each stop line. The following detection parameters were used: minimum headway (gap) = 1.2 s, detector length = 2.0 m. The speed reduction zone enabled to ensure realistic deceleration behavior.

3.2 Static vs. dynamic control

To evaluate the effectiveness of various control strategies, the first was designed and implemented a simulation scenario that compared static and dynamic intersection control. To facilitate the easier and faster identification of bottlenecks and patterns in a transportation network, thereby enabling faster and more informed decision-making, heat maps were utilized. They are a powerful visualization tool for traffic flow analysis, which uses a color gradient to intuitively highlight areas of high traffic density or congestion (often with warmer colors, such as red) versus areas with lower traffic (cooler colors, such as green). Color quantification is explained in the legends of the respective figures. The focus was solely on controlling the road intersection and did not interfere with railway traffic management. For the static control approach, a default traffic light plan was created (Figure 2) that defined fixed phases and the durations of green, yellow, and red intervals for each traffic direction. This plan was then refined based on observations of traffic behavior in a visual simulation and subsequent analysis of performance indicators, including average waiting times, queue lengths, and traffic flow. The fine-tuning process involved refining the signal intervals and phase sequencing to optimize intersection throughput and minimize vehicle delays in each direction.

Every change was verified within the simulation environment and evaluated based on quantitative metrics. This approach enabled to pinpoint the most appropriate static control parameters, adapting them to the specific input conditions of the simulation. Through a systematic analysis of traffic flow patterns and vehicle interactions at the intersection, a foundation for effective traffic management was established. This foundation

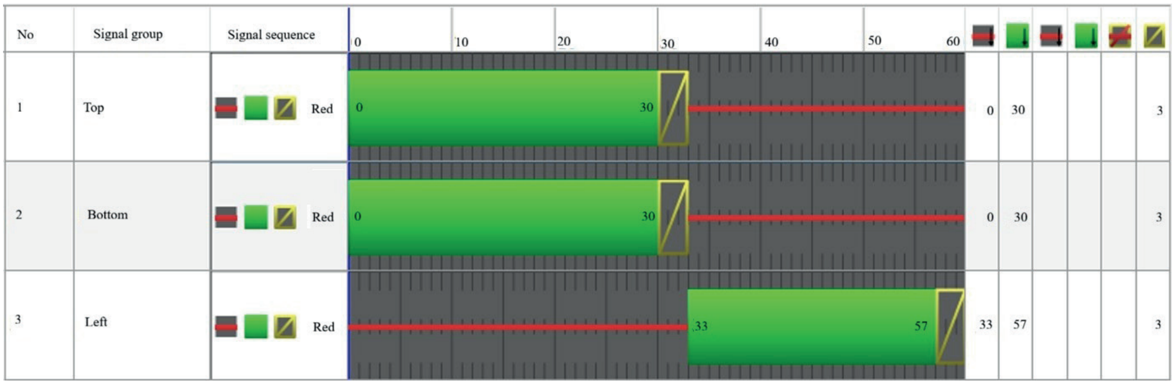

Figure 2 *Static Control Phasing*

Table 2 *Phase distribution for the intersection from Figure 1*

	TOP	BOTTOM	LEFT
Stage_1	Green	Red	Red
Stage_2	Red	Green	Red
Stage_3	Red	Red	Green

establishes essential elements, including signal timing, vehicle detection thresholds, and effective emergency response strategies. To enhance intersection performance and ensure its success under various conditions, it is essential to incorporate key elements effectively. Their integration increases both efficiency and adaptability to different situations. Modifying these parameters, based on realistic simulations, provided insights into the performance of static control versus adaptive systems, which further shaped our findings on traffic efficiency and safety outcomes. Even with meticulous tuning, it was clear that the static control, owing to its unchangeable nature, was unable to adequately respond to dynamically fluctuating traffic volumes. Thus, static control results in uneven utilization of the intersection capacity in certain situations.

For dynamic control, the original model needed to be extended with detection devices in the individual arms of the road network near the signals. These vehicle detectors provided continuous monitoring of the traffic situation, providing crucial input data for dynamic changes in the traffic light phases. Their correct placement and detection parameters were decisive for the effective functioning of the adaptive control system. For the control, three primary phases were defined to ensure the intersection's throughput based on the traffic load from different directions. The movements were organized into distinct phases, as described in Table 2.

Subsequently, a traffic signal control algorithm was implemented (Figure 3) that, in real-time, detected the presence of vehicles on each branch of the intersection using the detectors above. The primary objective of the algorithm was to ensure smooth traffic management with minimal waiting times, while also preventing the inefficient extension of phases. The logic of the algorithm was founded on two primary conditions for transitioning to the next phase *(Stage_active(n))*. The current phase cleared when the system detected no waiting vehicles on the served approach *(Headway(n)>gap)*, initiating a transition to the next phase through an interstage *(Interstage(n,m))*. Reaching the maximum allowed green phase time *(T_green(n)>MaxGreen)*. If vehicles were still present but the preset maximum interval for the phase had elapsed, the algorithm would also initiate a transition to the next phase to avoid unfairly favoring one traffic direction. For the adaptive control strategy, the following default timing constraints and logic parameters were applied: min green time = 8 s for all phases, max green time = 35 s for the main road phases, 25 s for the side road phase, yellow interval = 3 s, all-red interstage = 1 s.

Thus, the algorithm ensured dynamic and balanced intersection control that could flexibly react to current traffic conditions. For the next implementation phase, the control algorithm was extended to include a reaction to approaching trains, drawing inspiration from the TPS-DT algorithm. This approach provides priority control for the intersection when a train is in the vicinity, thereby minimizing the risk to traffic safety. The algorithm was specifically designed as follows: when a train was detected by a sensor located at a sufficient distance from the LC, two parallel actions were automatically initiated: closure of the LC entry was achieved by activating the barrier mechanism, thereby physically preventing other vehicles from entering the crossing; intersection control was switched to phase 3, which opened the exit direction from the LC (LEFT direction). This step enabled the clearing of the crossing of any trapped vehicles, thereby minimizing the risk of a collision with the approaching train. Once a predefined time interval had passed (sufficient to clear the crossing), control was automatically switched back to phase 1, which restored standard intersection operation. Phase 3 was also temporarily removed from

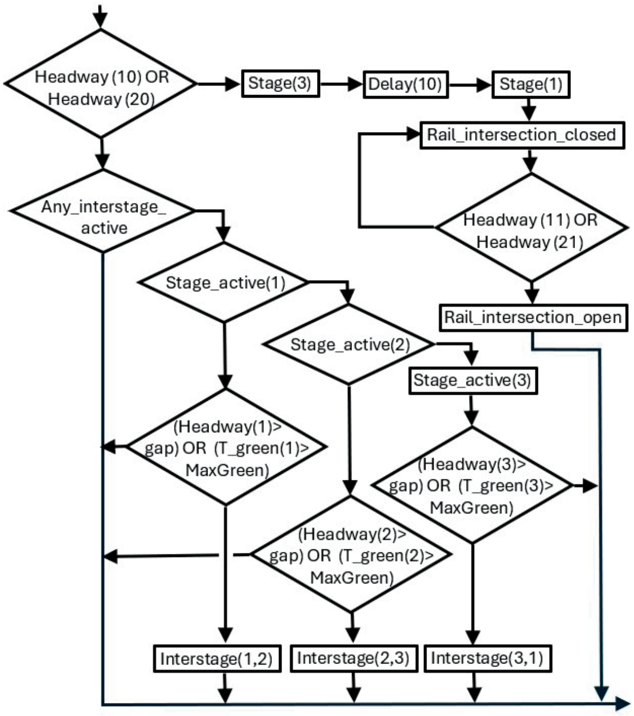

Figure 3 *Diagram of dynamic intersection control*

the control sequence to avoid its needless activation while a train was passing.

This special mode stayed active until the train passed the exit detector located after the crossing. The detector signaled that the crossing was clear and safe, enabling the full resumption of standard dynamic control, including all three phases. Using simulated data, heat maps were generated showing the average vehicle speed in specific sections for both static and adaptive intersection control scenarios. Each scenario was simulated multiple times to mitigate the impact of random deviations and enhance the reliability of our findings. The resulting speed values were subsequently averaged. Vehicle arrivals were modeled stochastically during the simulations to ensure more realistic and variable traffic conditions. The resulting visualizations (Figure 4) clearly show a difference between the two control approaches. Whereas the static control often causes significant vehicle slowdowns and congestion, adaptive control proved capable of reacting more effectively to real-time traffic conditions.

With the static control, it is evident that the two main directions, which are significantly more congested than the side approach intersected by the railway, are subject to greater restrictions. This situation is reflected in lower average speeds and a higher percentage of red segments on the heat map, which signifies more frequent and prolonged vehicle stops. Conversely, the dynamic control clearly shows that vehicles in the principal directions stop less often and for shorter periods, resulting in higher average traffic speeds. This situation is well visualized on the heat map as a larger area of green, with a substantially lower presence of red segments that would indicate slowdowns or stops. The differences between static and dynamic control were confirmed by a quantitative analysis of the simulation data (Figure 5). One can conclude that dynamic intersection control resulted in a notable improvement in several key traffic parameters.

For the main directions with the heaviest traffic, the average queue length significantly decreased under dynamic control compared to the static mode, dropping from 21.96 meters to 11.71 meters. This reduction suggests that vehicles in these directions were handled more quickly and fluidly, thus decreasing their buildup before the intersection. By implementing the adaptive algorithm, a reduction of over 46% in average queue length was achieved, which directly impacted other monitored parameters (Table 3).

The maximum recorded queue length (*maxQlenght*) was reduced from 178.13 m (static control) to 107.63 m (dynamic control), marking a significant decrease in the most severe traffic bottlenecks. The average vehicle delay *(VehDelay)*, which measures the time required by the vehicle to pass through the intersection, decreased from 48.71 seconds to 32.31 seconds. The delay *(StopDelay)*, which represents the waiting time due to a mandatory stop, decreased from 28.39 seconds to 22.15 seconds. The average number of stops per vehicle *(StopCount)* was reduced from 3.82 to 1.01, demonstrating significantly smoother vehicle movement within the intersection. The CO_2 emissions, a crucial indicator of environmental sustainability, were reduced from 493.51 g to 267.13 g per simulated unit of traffic. The results indicate

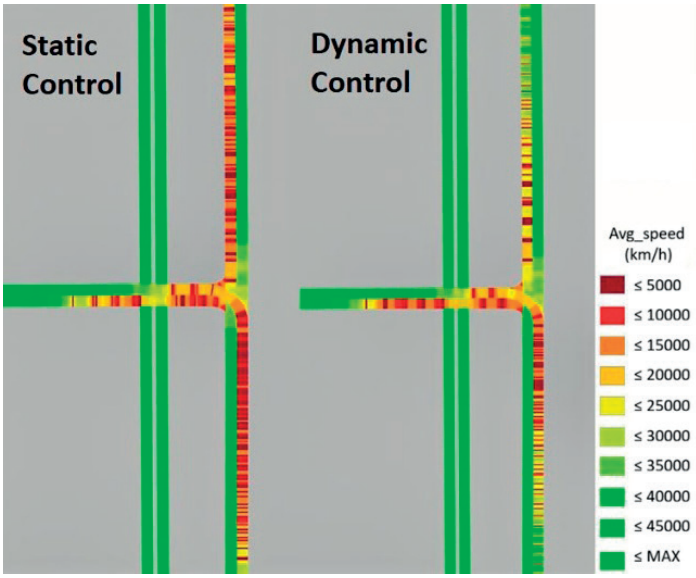

Figure 4 *Comparing traffic smoothness using the heat map visualizations*

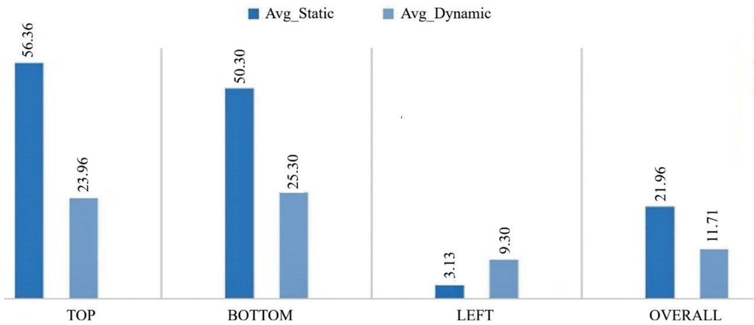

Figure 5 *Average queue length per direction in meters*

Table 3 *Data from simulations*

	BOTTOM	DYNAMIC
avgQlenght (m)	21.96	11.71
maxQlenght (m)	178.13	107.63
VehCount (-)	161.00	176.00
VehDelay (s)	48.71	32.31
StopDelay (s)	28.39	22.15
StopCount (-)	3.82	1.01
CO_2 (g)	493.51	267.13

that dynamic control, when implemented, significantly improves the performance of the traffic system at the modeled intersection. A positive environmental impact was also observed through lower emissions. These insights confirm that dynamic control is a more effective approach than static control, which does not respond adequately to real-time changes.

3.3 Analysis of the LC distance impact

For the following scenario, the same base road network model as before was utilized, but the focus shifted to varying the distance of the railway track from the intersection. Three different scenarios were modeled with the track located approximately 22, 50, and 80 meters from the intersection. The primary objective of this analysis was to evaluate the impact of this change on traffic flow and the frequency of collisions in the area. The results allowed to quantify the adverse effects of the railway crossing depending on its distance. They also provided a basis for proposing optimization measures to reduce traffic losses under such complex conditions. Throughout the simulations, the following parameters were systematically tracked: traffic flow (visualized using a heat map); number of potential collisions per hour; and spatial distribution of risk zones around the intersection. With the railway track approximately 22

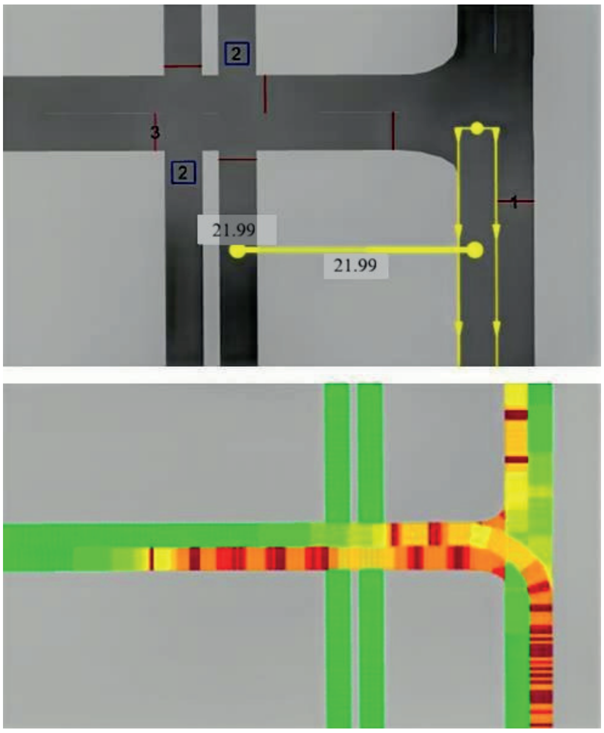

Figure 6 The heat map for a crossing distance of 21.99 m from the road

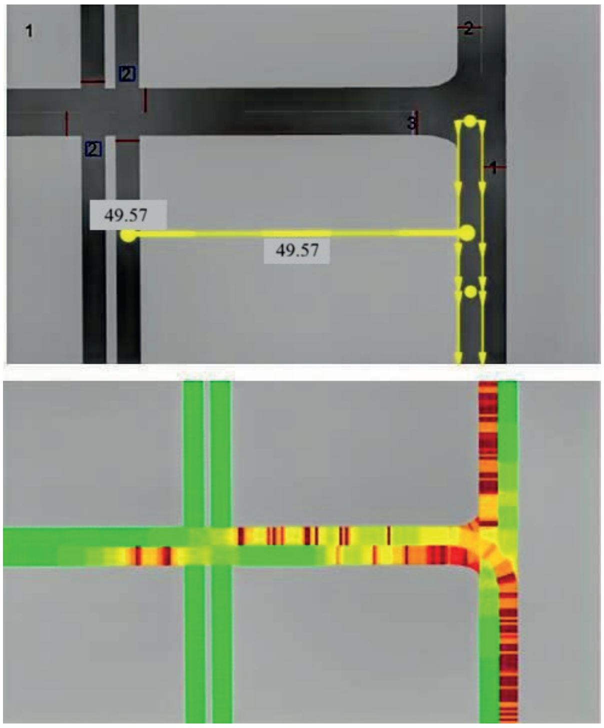

Figure 7 The heat map for a crossing distance of 49.57 m from the road

meters from the intersection, we recorded 12 collision situations per hour. A significant concentration of red and orange fields in Figure 6 indicates a high rate of conflicts and reduced traffic flow.

When the track distance was extended to approximately 50 meters, the number of collision incidents decreased to 6 per hour. The distribution of risk zones improved slightly; the red areas are less extensive and primarily concentrated near the intersection (Figure 7). The greater distance of the track allows vehicles waiting for a train to pass to encroach less often upon the intersection, which improved the organization of other road users' movements and reduced the number of dangerous situations.

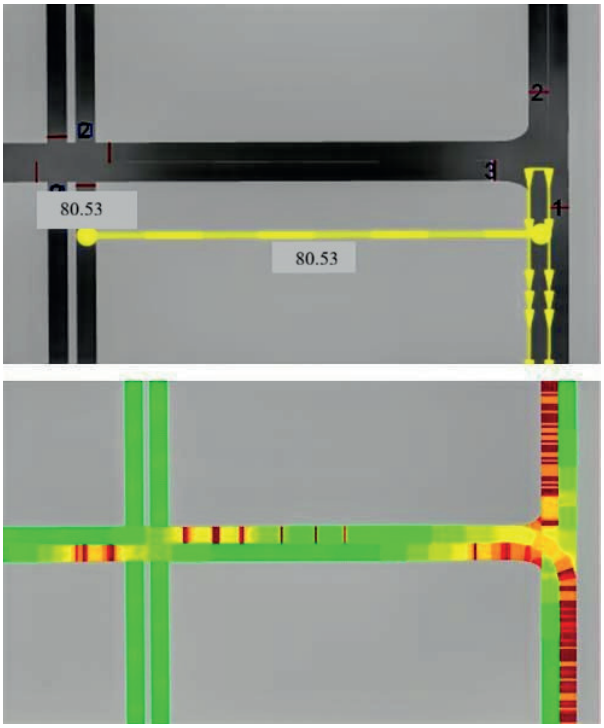

Figure 8 The heat map for a crossing distance of 80.53 m from the road

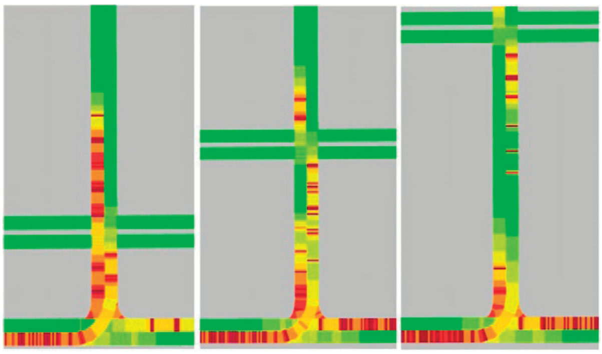

Figure 9 *Comparison of heat maps for considered crossing distances (increasing from left to right)*

The best results were achieved with the railway track at approximately 80 meters from the intersection, where the lowest number of collision incidents was recorded, only 4 per hour. In this case, the heat map (Figure 8) shows a significant improvement in traffic flow, with the majority of the area appearing green. This color represents a harmonious flow of traffic, ensuring minimal conflicts and seamless vehicle movement. In this kind of environment, transportation operates smoothly and effortlessly. The extended track length provides abundant space for vehicles to queue safely in front of the crossing, keeping the intersection clear. This thoughtful design guarantees a smooth and secure traffic flow, even if the barriers are lowered.

The analysis clearly shows that increasing the distance of the railway track from the intersection has a positive impact on traffic safety and flow. At shorter distances, intersections and LCs often overlap, leading to conflict situations, traffic congestion, and an increased risk of collisions. The greater distance enables more effective vehicle distribution and better traffic management when the LC is closed (Figure 9). When designing or renovating the intersections near a level crossing, increasing the distance between them improves both safety and traffic flow.

The perfect distance promotes safe vehicle gatherings, ensures smooth traffic flow, and significantly reduces the likelihood of collisions.

4 Conclusions

Managing the road intersections near railway LCs involves complex multidisciplinary challenges that require the integration of safety, traffic, technological, and environmental considerations. In this study was demonstrated that modern simulation tools provide a robust and flexible environment suitable for analyzing, testing, and optimizing control strategies for complex traffic nodes. Simulation models enable the precise analysis of traffic flows, verification of system behavior in various scenarios, testing of different control strategies, and the design of solutions that minimize collision risks, reduce traffic congestion, and improve overall traffic fluidity. The proper configuration of traffic signals together with synchronization between road and rail traffic is essential if we want to prevent critical situations and ensure the safety of all road users. Given the ability of simulation tools to react quickly to changes in infrastructure or traffic load, these tools provide the long-term sustainability and adaptability for the proposed solutions. At the same time, it was demonstrated that effective and dynamic control also has significant environmental benefits. Reduced waiting times and elimination of unnecessary stops result in lower exhaust emissions and noise, improving air quality and the environment in urban areas. As the comparison between the static and dynamic control shows, modern adaptive approaches, which utilize sensors, data analysis, and artificial intelligence, significantly outperform traditional (and less expensive) static models, especially under complex and changing traffic conditions. Based on the results obtained, it can be unequivocally stated that the implementation of dynamic and adaptive control represents a significant advancement over traditional static approaches. These modern approaches enable the optimization of traffic time, increase intersection throughput, enhance the comfort of road users, and simultaneously contribute to environmental sustainability.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] LIN, P.-S., WANG, Z., WANG, Q., GUO, R. Coordinated pre-preemption of traffic signals to enhance railroad grade crossing safety in urban areas and estimation of train impacts to arterial travel time delay. *CUTR Faculty Journal Publications* [online]. 2014, **144** [accessed 2026-04-17]. Available from: https://digitalcommons.usf.edu/cutr_facpub/144

[2] MICHALIK, R., JANOTA, A., NEMEC, D., HRUBOS, M. Co-operation of the control logic of the T-shape road intersection and the near railway level crossing. *Transport Research Procedia* [online]. 2019, **40**(2019), p. 1465-1472 [accessed 2026-04-17]. ISSN 2352-1457, eISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2019.07.203

[3] WANG, J., GUO, X., ZANG, X. Efficient and safe strategies for intersection management: a review. *Sensors* [online]. 2021, **21**(9), 3096 [accessed 2026-04-17]. eISSN 1424-8220. Available from: https://doi.org/10.3390/s21093096

[4] URBANIK, T., TANAKA, A. *Traffic signal preemption at intersections near highway - rail grade crossings* [online] [accessed 2026-04-17]. Washington, DC, USA: The National Academies Press, 2017. ISBN 978-0-309-38995-2. Available from: https://doi.org/10.17226/24769

[5] CHEN, Y., RILETT, L. R., WU, Z. Advanced transition preemption strategy for signalized intersections near highway-rail grade crossings with dual tracks. *Journal of Advanced Transportation* [online]. 2022, **2022**, 6697830 [accessed 2026-04-17]. eISSN 0197-6729. Available from: https://doi.org/10.1155/2022/6697830

[6] CHO, H. *Preemption strategy for traffic signals at intersections near highway-railroad grade crossings* [online] [accessed 2026-04-17]. Ph.D. dissertation. Texas, USA: Texas Transportation Institute, Office of Graduate Studies of Texas A&M University, 2003. Available from: https://hdl.handle.net/1969.1/406

[7] CHO, H., RILETT, L. R., PARK, D. Analysis of performance of transitional preemption strategy for traffic signal near at-grade railway grade crossing. *KSCE Journal of Civil Engineering* [online]. 2011, **15**(3), p. 569-579 [accessed 2026-04-17]. eISSN 1976-3808. Available from: https://doi.org/10.1007/s12205-011-1174-0

[8] MIRCHANDANI, P. B., LUCAS, D. E. Integrated transit priority and rail/emergency preemption in real-time traffic adaptive signal control. *Journal of Intelligent Transportation Systems* [online]. 2004, **8**(2), p. 101-115 [accessed 2026-04-17]. ISSN 1547-2450, eISSN 1547-2442. Available from: https://doi.org/10.1080/15472450490437799

[9] WU, G., LI, I., ZHANG, W-B., JOHNSTON, S., LI, M., ZHOU, K. SPRINTER rail: grade crossing/traffic signal optimization study. California PATH Research Report UCB-ITS-PRR-2009-21 [online] [accessed 2026-04-17]. Berkeley: Institute of Transportation Studies University of California, 2009. ISSN 1055-1425. Available from: https://escholarship.org/content/qt1gq7c0bq/qt1gq7c0bq.pdf

[10] KIM, I., LARUE, G. S., FERREIRA, L., RAKOTONIRAINY, A., SHAABAN, K. Traffic safety at road - rail level crossings using a driving simulator and traffic simulation. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2015, **2476**(1), p. 109-118 [accessed 2026-04-17]. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2476-15

[11] VEERARAGAVAN, S., ROSLY, A. B., KAMAL, M. A. S., SUSILAWATI, S., TAN, C. P., YAMADA, K. Optimal vehicle control to improve traffic flow at railway level crossings. In: 62nd Annual Conference of the Society of Instrument and Control Engineers SICE: proceedings. IEEE. 2023. ISBN 9798350318425, p. 198-203. Available from: https://doi.org/10.23919/SICE59929.2023.10354108

[12] JACOB, M., BENEKOHAL, R. F. Quantifying the extent to which connected and autonomous vehicles reduce accidents at railroad grade crossings: a machine learning approach. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2022, **2676**(6), p. 731-742 [accessed 2026-04-17]. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.1177/03611981221076116

[13] Act on Road Traffic and Amendments and Supplements to Certain Acts. Act No. 8/2009 Coll. 2009.

[14] Act on Railways and Amendments and Supplements to Certain Acts. Act No. 513/2009 Coll. 2009.

[15] Railway Operations Rules. ZSR Z1. 2011.

[16] Railway Crossings and Passages. ZSR Z12. 2011.

[17] Accidents and Extraordinary Events. ZSR Z17. 2025.

[18] Report on railway safety and interoperability in the EU - European Union Agency for Railways [online] [accessed 2026-04-17]. Publications Office of the European Union. Rep. no. TR-05-24-284-EN-N. 2024 Available from: https://data.europa.eu/doi/10.2821/64343

[19] Multimodal Traffic Simulation Software - PTV Group [online]. 2025. Available from: https://www.ptvgroup.com/en/products/ptv-vissim