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Simulation-Based Evaluation of a New Integrated Intersection Control Scheme for Connected Automated Vehicles and Pedestrians

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Abstract

In a fully connected traffic environment with automated vehicles, new traffic control strategies could replace traditional traffic signals at intersections. In recent years, several studies about reservation-based intersection control strategies have been published, and a significant increase in capacity was shown. In the strategies presented so far, other road users usually play a minor role or are not considered at all. However, many use cases of automated driving occur in urban environments, where pedestrians and bicyclists play a major role. In this paper, a novel strategy for integrating pedestrians into automated intersection management is introduced and compared with a fully actuated traffic (AT) signal control. The presented control consists of a first-come, first-served strategy for vehicles in combination with an on-demand traffic signal for pedestrians. The proposed intersection control is explained, implemented, and tested on a four-leg intersection with several lanes coming from each direction. It dynamically assigns vehicles to lanes, and vehicles follow a protocol that enables cooperative lane-changing on the approach to the intersection. Demand-responsive pedestrian phases are included in such a way that predefined maximum pedestrian waiting times are not exceeded. A set of demand scenarios is simulated using a microsimulation platform. The evaluation shows that the presented control performs significantly better than the AT control when considering low, medium, and high traffic demand. Pedestrian waiting times are slightly improved and at the same time vehicle delays are substantially decreased. However, the control needs to be improved for scenarios with a very high vehicle demand.

Continuous development of in-vehicle sensors along with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications has had a significant impact on the increase of automated driving functions. Connected and automated vehicles (CAVs) have a great potential to improve future traffic safety and increase traffic capacity. This potential does not only come from shorter reaction times and decreased following distance, but also from the possibility of developing new traffic control strategies (*1*). Current traffic control strategies, especially at intersection zones, are designed to accommodate human driving behavior. Therefore, intersections are currently managed by traffic signals and stop signs. Traffic signals alternate the right of way of different road users (e.g., cars, public transport, pedestrians) to coordinate conflicting flows. Depending on the traffic demand, traffic signals can be inefficient and long waiting times can occur. Additionally, at signalized intersections, vehicle turning movements represent a considerable safety problem to pedestrians (*2*) which could be alleviated with a future use of CAVs.

In recent years, several intersection management schemes for a penetration rate of 100% CAVs have been proposed (*1*, *3*, *4*). Most of these management strategies include a centralized control unit or intersection manager that provides each approaching vehicle with a conflict-free trajectory. The idea was analyzed in several research papers and a significant increase in capacity was shown (*1*, *3*). Different newspapers took on the concept, presented these simulations and envisioned a "future

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without traffic signals" (*5*). However, in contrast to traditional traffic signals, other road users such as human-driven vehicles, pedestrians, and bicyclists are usually not considered in these intersection control strategies. Pedestrians and bicyclists play an important role, especially in urban transportation. In Germany, non-motorized traffic has a share of 33% among all transportation modes considering trips, and a share of 6% considering traveled person kilometers (*6*). In the U.S.A., walking and bicycle trips account for 11.5% of all trips undertaken (*7*). In relation to current climate and air quality challenges, the level of service for these emission-free modes of transportation should not deteriorate when CAVs enter the operations.

This paper briefly describes other relevant studies about this topic and introduces a new control strategy for integrating pedestrians into a demand-responsive automated intersection control. The core of this new, pedestrian-friendly strategy is a defined maximum waiting time for pedestrians, which must not be exceeded. The control algorithm builds on strategies that were previously developed by the authors and tested on a small intersection (*8*). In this paper, a major urban intersection with several lanes from each direction is simulated using the microsimulation platform aimsun.next. To the best of the authors' knowledge, this is one of the first studies to evaluate and compare pedestrian operations in a futuristic automated environment with traditional pedestrian operations. The main objective is to present, implement, and evaluate this novel strategy which is compared with optimized fully actuated traffic signals for a set of different traffic demand scenarios.

The remainder of the paper is organized as follows. The second section gives an overview of related literature. In the third section the considered intersection and the control strategies for approaching vehicles and for the pedestrian signal are presented. The simulation specifications and demand scenarios are explained in the fourth section. In the fifth section the results of the study are shown, and in the final section conclusions and future research are given.

Literature Review

Several approaches to so-called cooperative or autonomous intersection management (AIM) have been proposed by authors coming from different fields of research. A good overview of the methods and assumptions is given by Chen and Englund (*4*). Most of the strategies consider passing through an intersection as a problem of discrete resource allocation where the objective is to allocate time slots and intersection space to vehicles for safe and efficient intersection passing. Two major types of AIM can be distinguished: centralized AIM involving an intersection controller and distributed AIM where the right of way is negotiated directly between vehicle agents following a certain protocol. While distributed AIM requires less infrastructure support and is more robust in relation to failures, a centralized intersection control unit can facilitate the negotiation process and optimize the efficiency of the intersection (*4*). The central intersection controller communicates with all approaching vehicles and receives relevant information from them, for example, origins, destinations, and earliest arrival times at the intersection. The control unit then allocates discrete space–time cells to approaching vehicles and sends them their assigned time slots or even an exact trajectory that they need to follow to cross the intersection without conflicts. The first notable implementation of reservation-based AIM was presented by Dresner and Stone (*1*). It has been followed up by several studies addressing similar concepts (e.g., *9*, *10*). Most of these approaches use a first-come, first-served (FCFS) strategy, but there are also some that propose different serving priority strategies, for example, in combination with economic incentives (*11*, *12*), with platoon-forming (*13*, *14*), or with a redefinition of lane assignment and lane direction (*15*).

AIM approaches usually focus on vehicle traffic, while the other road users are not taken into account in the studies presented above. Dresner and Stone presented an extension of their AIM strategy that allows non-connected vehicles as well as pedestrians and bicyclists to cross the intersection safely (*16*). However, their approach is not responsive to pedestrian demand and it does not focus on the level of service for pedestrians. This is in line with traffic signal planning; traditional signal timing objectives focus on minimizing vehicle delay and stops, which can lead to long waiting times for pedestrians (*17*, *18*). An additional problem when considering pedestrians in the presented AIM systems is that pedestrians are currently not connected to each other, to the other road users, or to the infrastructure. Therefore, their presence and desired destination are not easily predictable and it is not easy to inform them when they are given the right of way. The majority of research and development efforts considering pedestrians at future intersections currently focus on safety issues such as detection and warning (*4*). Some studies assume that pedestrians are going to be connected via mobile devices in the future (*19*, *20*). While this enables enhanced safety features, for example, through collision warnings, it cannot be assumed that everybody on the road will be connected and sending information about position and destination. The reasons for this opinion are the existence of privacy concerns and an unacceptable shift of responsibility from cars and drivers to the vulnerable road users. These concerns are also shared by others, see for example the responses from a recent survey of bicyclists (*21*). However, in this study, it is assumed that it is possible to include pedestrians in a demand-responsive intersection management system because they can be detected when they are present at the intersection. This is already technically feasible; the primary current detection mechanism for pedestrians is the use of pedestrian push buttons. In the last decades, automated detection technologies have been suggested as an alternative way to detect pedestrians, and some of them, including infrared, microwave, and image processing technologies, show promising results (*22*). Besides detecting pedestrian presence, these technologies can also capture the number of waiting pedestrians, track pedestrian movements on the street, and extend the crossing time (if necessary) (*18*). If pedestrians do not use a mobile device, they still have to be notified when they are given the right of way. While there are several approaches on how autonomous vehicles could communicate with pedestrians and display the right of way to them in the future (*23*), it is assumed here that bigger intersections (where pedestrians need to cross several lanes) will be equipped with a proper pedestrian signal infrastructure.

In a previous study, the authors presented and implemented a new reservation-based intersection management strategy for a small intersection zone with CAVs and pedestrians (*8*). It was shown that there are several ways to include pedestrians into an AIM while ensuring that predefined maximum pedestrian waiting times are not exceeded. Both the pedestrian and the vehicle level of service could be improved as compared with a fixed-time traffic signal control. However, that study considered a very small intersection with only one lane from each direction (*8*). While this simplified the development of the introduced control strategies, it also limited the degrees of freedom; vehicles coming from one direction had to enter the intersection zone in the exact order that they had entered the section, independent of their turning intentions.

This paper extends the aforementioned study by presenting an improved control strategy that is implemented and compared with a fully actuated traffic signal on a four-leg intersection with several lanes coming from each direction. The control assigns lanes dynamically and vehicles follow a protocol that enables cooperative lane-changing on the approach to the intersection. Demand-responsive pedestrian phases are included into the control in such a way that predefined maximum pedestrian waiting times are not exceeded and the number of vehicle–pedestrian conflicts (that needs to be resolved) is minimized.

Intersection Control Strategy

In this chapter, the conditions of the considered intersection are introduced along with the implemented control strategies, which are based on a combination of AIM for CAVs and demand-responsive traffic signals for pedestrians.

Example Intersection Zone

To develop and test the implemented intersection control, an example four-leg intersection zone, as shown in Figure 1, is considered. The intersection has a main road with three lanes in east–west directions and north–south minor road approaches, each with two lanes. There are signalized pedestrian crossings at each leg of the intersection. The major road facilitates a pedestrian refuge island, see Figure 1*c*. For the traditional traffic signal control scenarios, the lane assignment is fixed and relatively restricted as shown in Figure 1*a*: turning movements are only allowed from the leftmost or rightmost

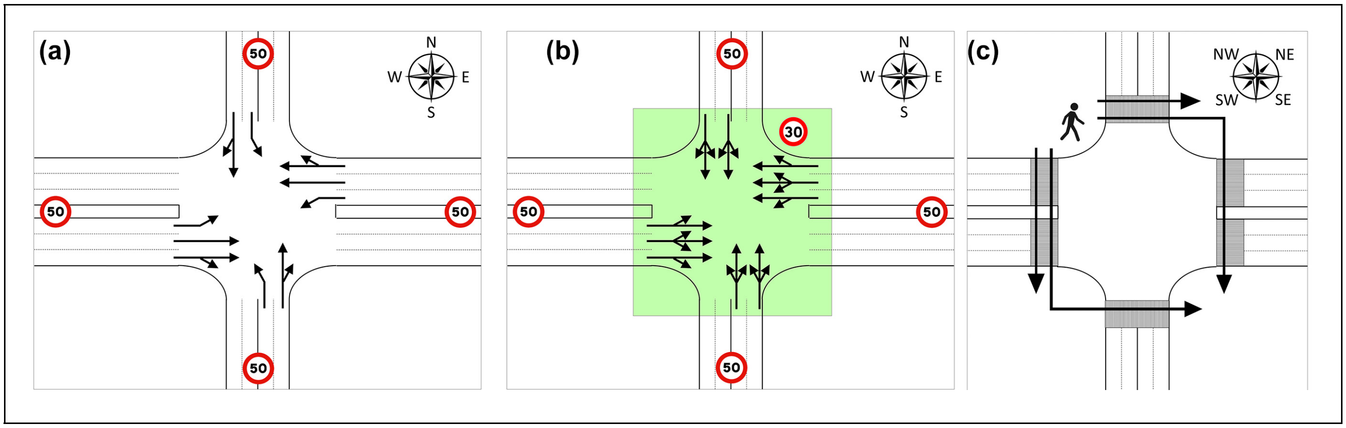

Figure 1. Intersection geometry of considered intersection with lane assignment and pedestrian crossings for different scenarios: (*a*) lane assignment for the traffic signal control scenario, (*b*) lane assignment for the automated intersection control scenario, and (*c*) pedestrian crossings.

lanes, respectively, and left-turning vehicles have their own lane. This kind of lane assignment is commonly seen in the field and it enhances the safety and efficiency of intersection operations. For the AIM, the lane assignment can be more flexible, and turning movement does not have to be restricted to the side lanes, as conflicting trajectories are resolved by the intersection controller. Therefore, a new lane assignment with all possible turning movements is presented in Figure 1*b*.

It can be observed that the speed in the intersection zone is reduced to 30 km/h for the AIM case. On the one hand, it is important that vehicles enter the intersection with a certain minimum speed to avoid blocking the intersection area for too long. If a vehicle is slowed down when approaching the intersection area, it thus accelerates again before reaching the required speed, see, for example, Niels et al. (*8*). On the other hand the speed cannot be too high as the vehicle needs to be able to react to the pedestrian detection system and come to a full stop if necessary. Thus, a speed limit of 30 km/h is a good trade-off between safety (primarily for pedestrians) and efficiency of the traffic stream.

Architecture of the Intersection Control

The intersection control strategy presented in this paper works with a discretization of space and time. Therefore, the considered intersection is divided into several mutually exclusive conflict areas, as shown in Figure 2*a*. Dividing an intersection into a grid of conflict areas is common when developing AIMs, see for example, Dresner and Stone (*1*). In the present case, not only the conflicting movements of vehicles are considered, but also the conflicts between vehicles and pedestrians. This means that both vehicles and pedestrians reserve the cells of the intersection zone that they want to pass through, and only a single vehicle or a group of pedestrians is allowed to occupy a single conflict area at any particular time interval. Thus, approaching vehicles and the pedestrian requests (indicating either pedestrians who want to cross or those who are currently crossing) communicate with the intersection controller as shown in Figure 2*b*. The intersection controller collects relevant information from approaching vehicles and reserves a time slot for them. When pedestrians arrive at the intersection, the controller schedules a green phase for the requested crosswalk and returns green to the pedestrian signal head. If necessary, vehicles are rescheduled and receive a new time slot. The control calculates speeds for vehicles in such a way that they arrive at the intersection exactly on time. The approaching vehicles communicate with surrounding vehicles to ensure safety gaps and facilitate cooperative lane changing. The following assumptions are made to develop and implement this control strategy:

- The dynamic vehicle information (i.e., position, current speed, and turning information) is available as soon as the vehicle enters a range of 300 m from the intersection. This is possible with current state-of-the-art dedicated short-range communication (DSRC) systems (*24*). V2V and V2I communication is assumed to be ideal, that is, possible packet loss and latency are ignored.
- All vehicles have the same dimensions and dynamic/kinematic characteristics.
- Vehicles can communicate with surrounding vehicles and exchange current positions and speed. When adjusting their speed, they follow a protocol that allows for cooperative lane changing.
- Pedestrians are detected when they are already at the intersection. Their right of way is displayed to them via pedestrian signal heads.
- Pedestrians are assumed to cross the intersection with a walking speed of 1.2 m/s (*25*). An additional clearance time is assigned and detection systems ensure that the pedestrian crossing is cleared before a vehicle is allowed to cross. If pedestrians are still on the street, the clearance time is extended. Approaching vehicles are slowed down (and eventually stopped, if needed), and a new slot for crossing the intersection is assigned to them, if necessary.
- The default setting of the pedestrian signal is green, that is, if no vehicle is assigned to cross a pedestrian crossing within the next seconds, the corresponding traffic signal shows a green light for pedestrians.

In the following subsections, the control strategies are explained for approaching vehicles and for pedestrians at the intersection separately.

Automated Intersection Control for Vehicles

In principle, an FCFS policy as explained by Tachet et al. (*13*) is implemented for the intersection shown in Figure 2*a*. When entering the communication range, each vehicle v approaching the intersection zone sends relevant information including its current position, speed, and turning movement to the intersection manager. Depending on its current lane and desired destination, the intersection manager calculates the earliest possible arrival time $t_0(v)$ for v at the intersection and reserves the first possible time slot that is available. It returns the reserved time slot $t^*(v)$ as well as the lane $l^*(v)$ that v needs to use to enter the intersection, and its leader vehicle *leader*(v). By *leader*(v) we denote the vehicle that is assigned to enter the intersection directly before v from the same lane. If a new vehicle v' signs up with the

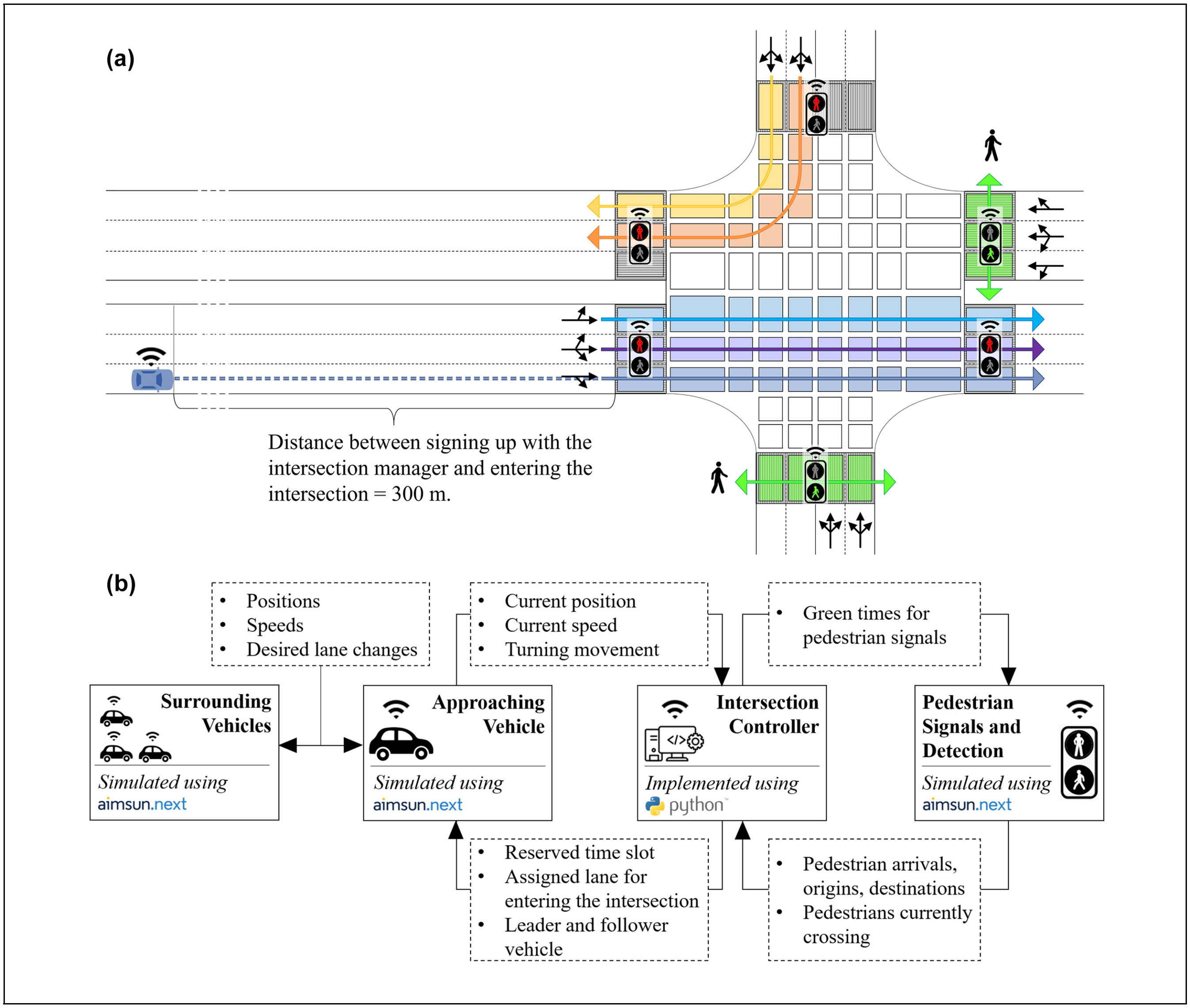

Figure 2. Division of the intersection zone into different cells and presentation of communication between vehicles, pedestrian signals, and the intersection controller: (*a*) geometry of intersection zone: division into cells and (*b*) flowchart of intersection control and communication to approaching vehicles and pedestrian signalization.

intersection manager and v is the leader of v', then v is notified that it has a follower, *follower*(v).

In contrast to other AIM approaches, the reserved time slots in this control are subject to change and vehicles can be rescheduled. Reasons for rescheduling the arrival time of vehicle v are various, including situations in which priority is given to pedestrians (the main focus of this paper), or to a specific vehicle or group of vehicles. It is also possible that v does not reach the intersection on time, for example, if the crossing time for pedestrians is extended because of slow pedestrian movement. Another difference compared with the other AIM studies is that vehicles can change lanes on the approach to the intersection. The intersection controller might even assign them to enter the intersection from a different lane than the one that they are currently in. This gives the controller a higher flexibility, especially if some areas are reserved for pedestrians. For example, if the pedestrian crosswalk on the southbound approach is reserved for pedestrians, vehicles driving from west to east will not be assigned on the rightmost lane if there are right-turning vehicles waiting for the pedestrian phase to pass. On the other hand, necessary lane changes account for a higher uncertainty.

Because of computational complexity, the intersection controller does not calculate a complete trajectory for vehicles approaching the intersection. Therefore delays can occur if v or vehicles in front of v do not perform the

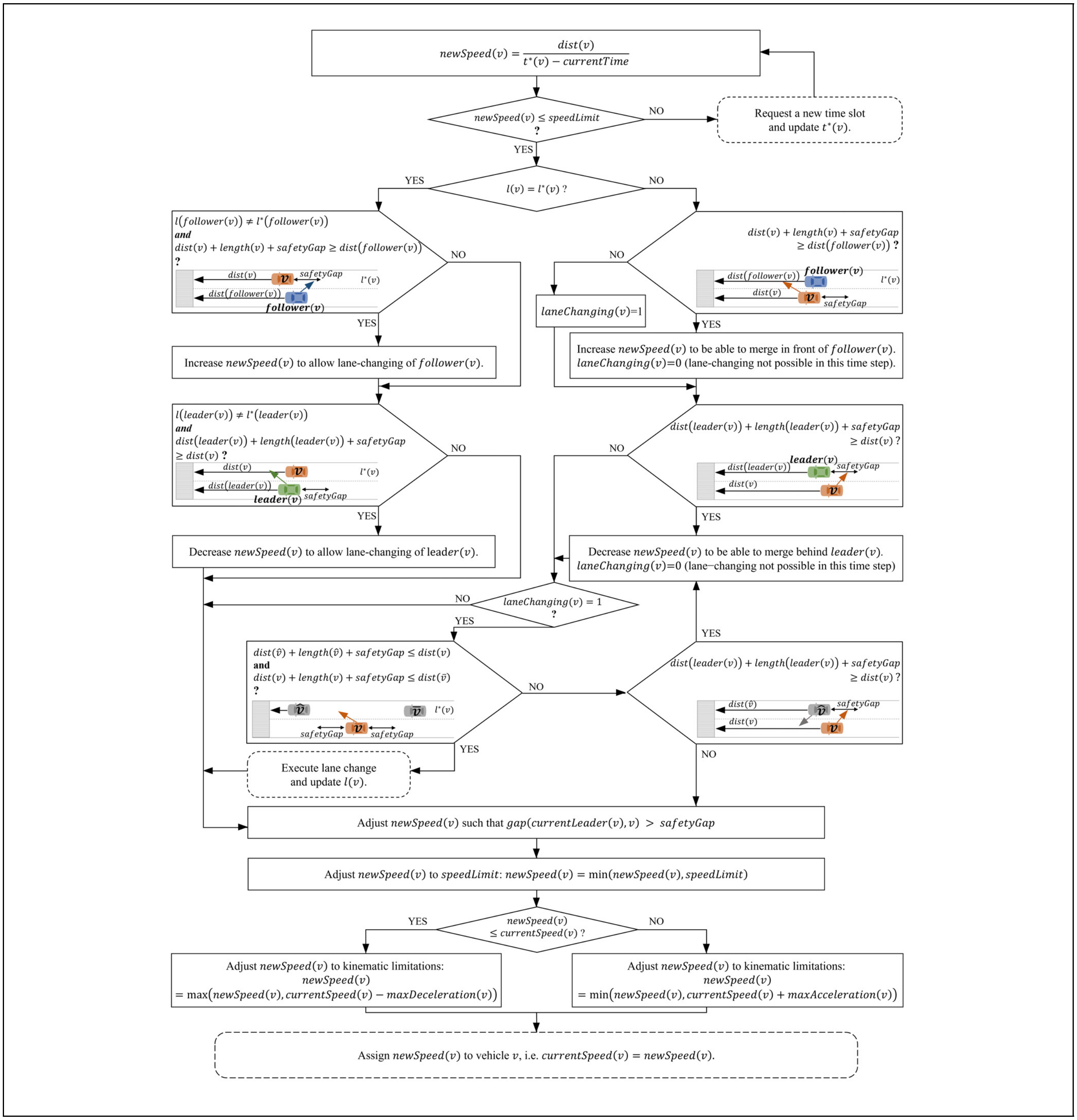

Figure 3. Flowchart for calculating the new speed of vehicle *v* in every time step.

lane-changing process on time. To avoid that, in each time step, each approaching vehicle adjusts its speed following the protocol shown in Figure 3 to enable cooperative lane changing. First of all, the optimal speed depends on the current distance $dist(v)$ from v to the intersection zone and the time left until the reserved time slot $t^*(v)$. If this optimal speed is above the speed limit, vehicle v will not reach the intersection on time and it needs to request a new time slot. Otherwise, the new speed is adjusted in several steps. Note that adjustments made at the end of the procedure overwrite adjustments made in the beginning. This does not result in alternate braking and accelerating, as the speed is only assigned to v after finishing every step of the procedure. V2V-communication is used to obtain dynamic information of the vehicles surrounding v. If v is already in the assigned lane, that is, $l(v) = l^*(v)$, then v checks if its assigned follower is already in the same lane or if it is beneficial to accelerate to allow $follower(v)$ to merge behind it. Afterwards, the same is done with $leader(v)$. In this case, it might be necessary for v to decelerate. If v is not yet in its assigned lane, the first steps look similar. It is important that $dist(leader(v)) < dist(v) < dist(follower(v))$ when v changes lanes. If, additionally, gaps are large enough, v can move to the next lane. The final steps represent adjustments of the speed according to the position and speed of the leading vehicle (directly in front of v), the speed limit, and the kinematic limitations.

Even though the lane assignment is flexible, as shown in Figure 1*b*, it is beneficial that left-turning vehicles use the leftmost lane and right-turning vehicles use the right lane. Turning movements from other lanes lead to a higher number of cell reservations and longer intersection crossing times. Therefore, turning vehicles are assigned to a lane other than their traditional turning lane (left- or rightmost lane, respectively) only if this reduces their delay by more than a defined threshold λ. Through movement can use any lane and always needs the same amount of time for passing the intersection. Lane changes can lead to delays on the approach to the intersection. Therefore, when assigning a time slot to a vehicle v that goes straight, then $l^*(v)$ differs from its current lane $l(v)$ only if this improves the arrival time for v by more than λ. This is done to avoid lane changes leading to a marginal improvement of travel time for a single vehicle. For simplicity, it is assumed that vehicles which register with the intersection manager are already in one of the lanes from which their desired movement is allowed. Additionally, it is assumed that vehicles which are currently in the rightmost lane are not assigned to the leftmost lane and vice versa; that is, only one lane change needs to be performed. If vehicles are rescheduled, their assigned lane as well as their leading and following vehicles can change.

On-Demand Traffic Signals for Pedestrians

While a vehicle reserves its time slot for crossing the intersection at least 30 s before its arrival, pedestrians are detected (by the detection system) only when they are at the intersection and ready to cross. Let $t_0(p)$ be the arrival time of pedestrian p at the intersection. It is assumed that pedestrians should wait no longer than a maximum pedestrian waiting time that can differ depending on their origin and destination. To provide enough flexibility for various pedestrian cases, an individual maximum waiting time $MWT(p)$ is assigned for a pedestrian p. In the following, the policy for reserving a time slot for pedestrians is described in several steps. If a pedestrian wants to cross the north or south approach, only one pedestrian crossing needs to be reserved, as shown in Figure 1*c*. This is the easiest case and will be described first. On the west or east approach, pedestrians need to pass two crosswalks with a median refuge island. Finally, pedestrians wanting to go to the opposite pedestrian corner have to cross two approaches. If it is assumed that the maximum waiting time is independent of personal characteristics and the number of pedestrians waiting to cross, it is not necessary to request a time slot for p if there is a pedestrian p' with the same origin and destination already waiting at the intersection. In this case, p benefits from p' already having requested a time slot, and p can cross together with p'. In the following, it is assumed that p arrives at the intersection and needs to request a time slot for crossing the street—at this point, it is irrelevant for the intersection control if p is a single pedestrian or a group of pedestrians.

Pedestrians Crossing the Minor Road (South or North Approach).

Let $c(p)$ be the pedestrian crossing that a pedestrian p wants to cross. All conflict cells of this crosswalk need to be reserved for the time $t_{\text{needed}}(c(p))$ that p needs to cross $c(p)$ plus an additional buffer time b, and the minimum green time g for pedestrian signals. While vehicles can reserve time slots only if all requested conflict cells are free, for pedestrians a maximum waiting time is guaranteed. This means that pedestrians have priority and, if necessary, they can be assigned time slots that were already reserved by vehicles. The respective vehicles are then rescheduled and obtain a new arrival time. To avoid vehicle rescheduling, this paper uses a novel approach that checks the number of pedestrian–vehicle conflicts depending on the assigned time slot. From all time slots between $t_0(p)$ and $t_0(p) + MWT(p)$, the time slot with the smallest number of conflicts is chosen. For a conflict cell $cell$ and a time slot $time$, let $x(cell, time)$ be equal to v if $cell$ is reserved by vehicle v at $time$, and 0 otherwise. The total number of conflicts resulting from assigning p to cross $c(p)$ at time t can then be calculated as:

$$conflict(c(p), t) = \sum_{cell \in c(p)} \sum_{t \leq time \leq \bar{t}} \{x(cell, time) > 0\}$$

$$\text{with } \bar{t} = \begin{cases} t + r + t_{\text{needed}}(c(p)) + b & \text{if pedestrian signal of } c(p) \text{ is currently green,} \\ t + g + t_{\text{needed}}(c(p)) + b & \text{else.} \end{cases} \quad (1)$$

This idea is illustrated in Figure 4*a*. Note that if the pedestrian signal is currently green, it is not necessary to consider the minimum green time g, but a shorter reaction time r is enough. If there is at least one conflict-free time slot within the maximum waiting time, that is, if there exists t with $t_0(p) \leqslant t \leqslant t_0(p) + MWT(p)$ and $conflict(c(p), t) = 0$, the earliest of these slots is reserved by p. Otherwise, vehicles need to be rescheduled. In this case, it is important to consider that vehicles which are scheduled to cross the intersection within the next seconds cannot be rescheduled. Therefore, an intersection manager reaction time $IMRT$ is defined. When looking for a time slot for p, the arrival time of conflicting vehicles must be greater than or equal to $t_0(p) + IMRT$. If vehicle v is scheduled to pass conflict cell $cell$ at $time$, that is, $x(cell, time) = v$, then $t^*(v) \geqslant time - t_{\text{cross}}$, where t_{cross} is the maximum time that vehicles need to cross the intersection. The intersection manager reaction time is small enough to avoid gridlocks, that is, $IMRT + t_{\text{cross}} < MWT(p)$. Now pedestrian p is assigned to cross at the time slot $t^*(p)$ with the smallest number of conflicts:

$$t^*(p) = \underset{t}{\operatorname{argmin}}(conflict(c(p), t))$$

subject to:

$$t_0(p) \leqslant t \leqslant t_0(p) + MWT(p)$$

$$t^*(x(cell, time)) > t_0(p) + IMRT$$

$$\forall\ cell \in c(p),\ t \leqslant time \leqslant t_0(p) + IMRT + t_{\text{cross}}. \tag{2}$$

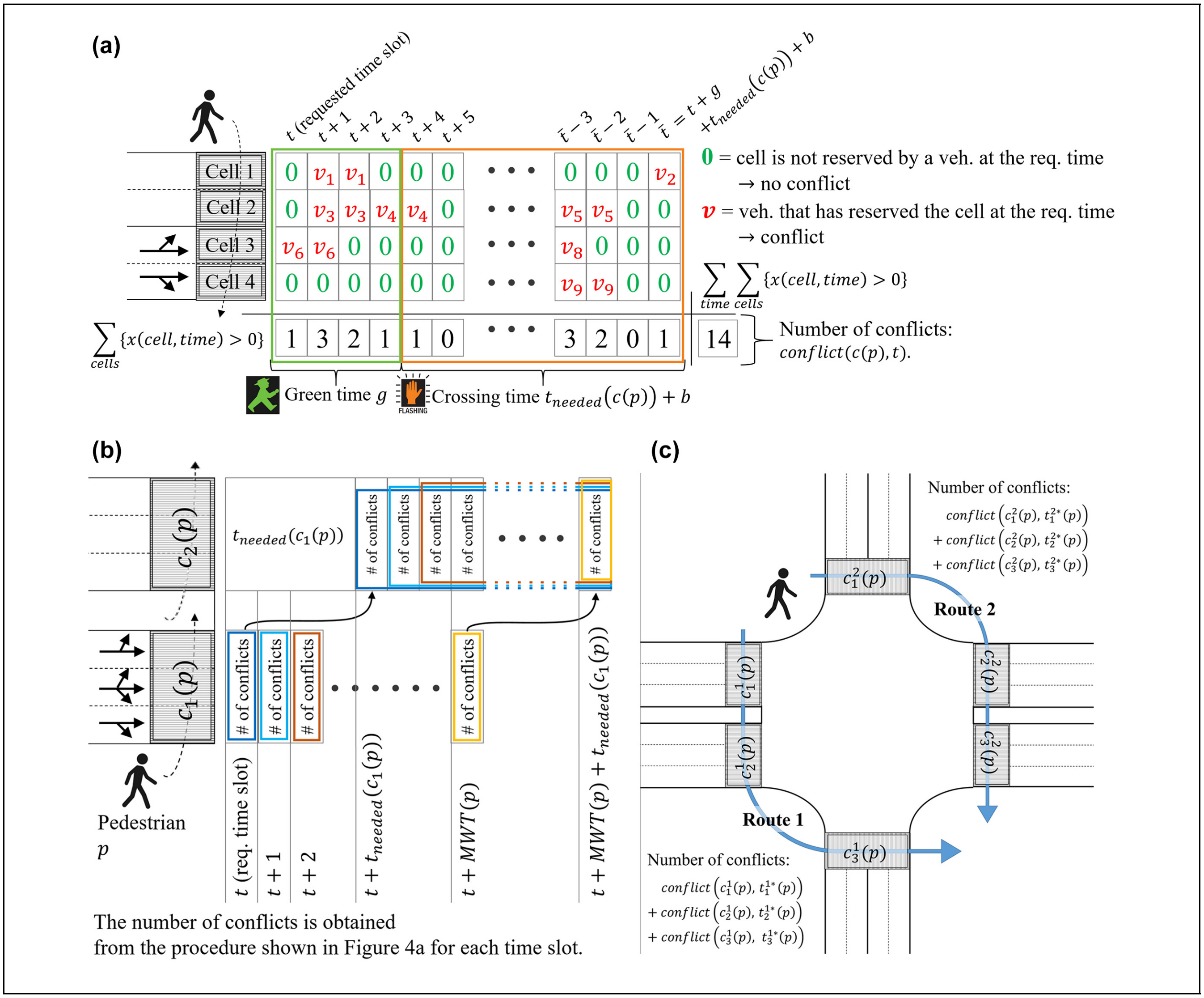

Figure 4. Explanation of the number of pedestrian–vehicle conflicts for different situations: (*a*) explanation of how the number of pedestrian–vehicle conflicts is derived for a specific crosswalk at a specific time slot, (*b*) explanation of the number of conflicts if a pedestrian crosses several crosswalks and (*c*) explanation of the number of conflicts if a pedestrian crosses diagonally.

If there are several time slots with the minimum number of conflicts that fulfill the requirements above, the earliest time slot among them is chosen and reserved for p.

Pedestrians Crossing the Major Road (East or West Approach). If a pedestrian p wants to cross the east or west approach, the crosswalk is divided into two parts that are separated by a median refuge island and are reserved individually. Therefore, let $c_1(p)$ be the first and $c_2(p)$ be the second sub-crossing that p needs to pass. Waiting times for p can occur at the origin or on the median refuge island—the requirement is that the sum of these waiting times does not exceed $MWT(p)$. The capacity of the median refuge island is assumed to be infinite. In principle, the strategy for reserving the crosswalks is similar to the case when pedestrians cross the minor road. The number of conflicts for passing the first and the second crosswalk are added up and the total number is minimized. Obviously, p can only cross $c_2(p)$ after reaching the median refuge island, as illustrated in Figure 4*b*. Now, pedestrian p is assigned to cross $c_1(p)$ at time slot $t_1^*(p)$ and $c_2(p)$ at time slot $t_2^*(p)$ with:

$$\begin{aligned}(t_1^*, t_2^*)&\\ = \underset{(t_1,t_2)}{\operatorname{argmin}}&(\mathit{conflict}(c_1(p), t_1) + \mathit{conflict}(c_2(p), t_2)) \qquad (3)\end{aligned}$$

$$\begin{gathered}\text{subject to:}\\ t_0(p) \leqslant t_1 \leqslant t_0(p) + MWT(p),\\ t_1 + t_{\text{needed}}(c_1(p))\\ \leqslant t_2\\ \leqslant t_0(p) + MWT(p) + t_{\text{needed}}(c_1(p)),\\ t^*(x(\mathit{cell}, \mathit{time})) > t_0(p) + IMRT\\ \forall\, \mathit{cell} \in c_1(p),\ t_1 \leqslant \mathit{time} \leqslant t_0(p) + IMRT + t_{\text{cross}},\\ t^*(x(\mathit{cell}, \mathit{time})) > t_0(p) + IMRT\\ \forall\, \mathit{cell} \in c_2(p),\ t_2 \leqslant \mathit{time} \leqslant t_0(p) + IMRT + t_{\text{cross}}. \qquad (4)\end{gathered}$$

Pedestrians Crossing to the Diagonal Corner of the Intersection. Pedestrians who want to cross to the opposite corner of the intersection pass the intersection in two consecutive perpendicular movements. To do so, they can take two routes as shown in Figure 4*c*. On each route they have to pass three crosswalks. The number of conflicts is obtained by extending Equation 3 by a third pedestrian crossing. Depending on the minimum number of conflicts on each of the routes, one route is assigned to them.

Obviously, not only the vehicles with conflicting movements are rescheduled. Rescheduling vehicle v does not only affect all vehicles driving behind v, but it also affects vehicles coming from the other directions. These vehicles might benefit from v not using its previously assigned time slot any more. Therefore, let $t^*(p)$ be the time reserved for pedestrian p at the crosswalk $c(p)$. Then all vehicles v with $t^*(v) \geqslant t^*(p)$ are rescheduled. For some vehicles, this rescheduling results in a shorter delay because they can use a better time slot than before.

Scenario Setup and Simulation

The presented AIM and the fully actuated traffic signal control (used for comparison) are simulated in the microsimulation platform aimsun.next. The AIM is implemented by using the Python programming language. The interface between the intersection control and the traffic model within the simulation is realized by using the aimsun.next's application programming interface (API) (*26*), as shown in Figure 2*b*. All vehicles that are within a distance of 300 m from the center of the intersection zone are controlled externally and their speeds are set by following the protocols explained in the previous section. Pedestrians are simulated by using the extension "Legion for Aimsun" with the default values for walking speeds and reaction times. Pedestrians are only allowed to cross the street when a pedestrian green light is shown. A demonstration video of the simulation can be found at https://vimeo.com/351534462 here (*27*).

Set of Demand Scenarios

Four different traffic demand scenarios and five levels of pedestrian activity (including one scenario without pedestrians for comparison) are simulated. They are presented in Table 1. Levels of low, medium, and high traffic demand are based on studies of similar-sized intersections (*15*, *28*), and levels of low, medium, and high pedestrian activity are set according to best practice for urban intersection planning in the U.S.A. Additionally, scenarios with very high vehicle and pedestrian activities are analyzed.

Fully Actuated Traffic Signal Control

The fully actuated signal control scenario (AT scenario) was implemented using the actuated traffic signal functionality of aimsun.next. The initial signal control plan was developed by using the VISTRO signal control optimization software (*29*) with the demand assumptions of the considered scenarios. The actuated control in aimusun.next follows the NEMA (National Electrical Manufacturers Association) standards (*30*). It is important to mention that the AT scenario is implemented in a fully protected environment, where permissive left-turn phasing and right-turns-on-red are not allowed. There are no exclusive pedestrian phases, but pedestrian signals

Table 1. Demand Values for the Different Scenarios

	Vehicle demand (traffic flow & turning movement)				Pedestrian activity			
	Southbound/northbound		Eastbound/westbound		Minor road	Major road	Diagonal	Total
Scenario	Vph (each)	Left right	Vph (each)	Left right	Ped/h (each)	Ped/h (each)	Ped/h (each)	Ped/h
Very high	1,200	20% 30%	1,800	15% 20%	35	21	7	126
High	1,000	20% 30%	1,500	15% 20%	25	15	5	90
Medium	800	20% 30%	1,200	15% 20%	15	9	3	54
Low	600	20% 30%	900	15% 20%	5	3	1	18

Note: ped/h = pedestrians per hour; vph = vehicles per hour.

Table 2. Parameter Values for the Microsimulation Experiments

Parameter	Value
Microsimulation and vehicle parameters	
Simulation step time	0.6 s
Vehicle length | vehicle width	4.0 m | 2.0 m
Maximum acceleration | normal deceleration | maximum deceleration	3.0 m/s ^{2} | 4.0 m/s ^{2} | 6.0 m/s ^{2}
Gap	0.7 s
Distance between vehicles at full stop	1.0 m
Reaction time for front vehicle at traffic signal	0.6 s
Speed limit acceptance	100.0%
Automated intersection management parameters (explained in Intersection Control Strategy section)	
Threshold λ for lane-changing and turning movement from middle lane	3.0 s
Minimum length of pedestrian green phase *g*	4.8 s
Pedestrian reaction time *r*	0.6 s
Time needed for pedestrians to cross the minor road	12.6 s
Time needed for pedestrians to cross one part of the major road	9.6 s
Buffer time for pedestrian crossing *b*	2.4 s
Intersection manager reaction time *IMRT*	4.8 s
Maximum waiting time for pedestrians crossing the minor road	36.0 s
Maximum waiting time for pedestrians crossing the major road	48.0 s
Maximum waiting time for pedestrians crossing to the diagonal corner	54.0 s
Traffic signal parameters (fully actuated traffic signal)	
Cycle time: minimum | maximum (input for optimization)	60.0 s | 180.0 s
Cycle time for low traffic demand (near-optimal)	138.0 s
Cycle time for medium traffic demand (near-optimal)	142.0 s
Cycle time for high traffic demand (near-optimal)	178.0 s
Cycle time for very high traffic demand (near-optimal)	180.0 s

are set concurrent to the vehicle signal phases. Cycle lengths returned by VISTRO for the different vehicular traffic demand scenarios are shown in Table 2.

Simulation Parameters

An overview of the parameters used for simulation settings and the control strategy is given in Table 2. To be able to compare the AIM with the AT control, the same simulation and vehicle parameters were used for all scenarios. They are comparable to the values used in Niels et al. (*8*). The variation of parameters is set to 0. The AIM parameters for pedestrian crossing times are set according to the dimensions of the intersection zone and pedestrian walking speeds. Maximum waiting times *MWT* for pedestrians are chosen in such a way that resulting average waiting times are similar for the AIM and AT scenarios. This makes it easier to compare the different control scenarios. *MWT* for pedestrians crossing the minor road is set to 36 s. Pedestrians who cross the major road need to cross two sub-crossings, therefore a larger (total) *MWT* of 48 s is assumed. For pedestrians passing to the diagonal corner of the intersection zone, *MWT* is set to 54 s.

Evaluation and Results

Simulations for each of the scenarios were performed for five random seeds for a duration of one full hour including 600 s of warm-up time. To evaluate the results of the investigated scenarios, we compare the average delays of vehicles (overall, i.e., not just stopped delays) and the waiting times of pedestrians.

Evaluation of Vehicle Delays

Once a vehicle leaves the intersection and reaches its desired speed, it does not experience delays any more. Therefore, the delay of vehicle v is approximated as the difference between the earliest possible arrival time of v at the intersection (denoted by $t_0(v)$) and the time it actually entered the intersection area (denoted by $t^*(v)$). The average delay of vehicles can then be computed as

$$\overline{delay(V)} = \frac{1}{|V|}\sum_{v \in V}(t^*(v) - t_0(v)) \tag{5}$$

where V is the set of all vehicles that cross the intersection during a simulated period of time.

Average vehicle delays for the base scenario with no pedestrian demand are shown in Figure 5*a*. Values are displayed for each origin–destination relation separately. It can be seen that the AIM control performs significantly better than the AT control for all considered traffic demand scenarios. Left-turning vehicles experience longer delays than through-movement and right-turning vehicles. Delays do not differ notably between vehicles approaching the intersection zone from different directions, which shows that both the AIM and the AT control are well balanced. While delays for the AT scenario increase almost linearly when moving to a higher demand scenario, the AIM control shows very low delays for the first three scenarios, but delays increase significantly when considering very high demand.

Figure 5*b* shows how vehicle delays change with pedestrian activity. Overall average vehicle delays for all simulation runs are presented along with the average delays of the best and worst simulation run. In the AT scenarios, a higher pedestrian activity has a slight impact on vehicle delays, because right-turning vehicles yield to pedestrians and thus block the entrance to the intersection for vehicles driving behind them. For the AIM scenario, it is straightforward to assume that a higher pedestrian activity can lead to longer vehicle delays, because the cells that pedestrians want to cross are exclusively reserved for them for several seconds. The impacts that pedestrian activities have on vehicle delays heavily depend on whether the intersection is operating close to its capacity limits. In the scenarios with low and medium traffic demand, pedestrian activity has almost no impact on vehicle delays. This changes for the scenarios with high traffic demand, however, vehicle delays are still significantly lower than in the AT scenario. Finally, results for the scenarios with very high vehicle demand show that integrating pedestrian operations into the AIM control leads to very long (and virtually unbounded) delays, indicating that the demand cannot be served in these scenarios.

If vehicle demand and pedestrian activity are low, pedestrians can mostly be integrated into the AIM without the need for rescheduling vehicles. If vehicle demand, pedestrian activity, or both, increase, however, pedestrian waiting times would exceed the defined *MWT* values and pedestrian priority is requested. Figure 5*c* shows the number of times that pedestrian priority was granted depending on the demand scenarios. If the traffic demand is very high, pedestrian activities lead to many vehicle rescheduling processes, which can significantly increase vehicle delays. In this case, it might be necessary to increase the assumed *MWT* or change the priority policy (if there are several time slots with the minimum number of conflicts, instead of assigning the first one to the pedestrian, a later time slot could be assigned).

While the considered very high demand goes beyond demand levels considered in other studies, it must be noted that the AT control shows better results in these scenarios. It has already been suggested by some researchers that FCFS controls are most beneficial in rather low to medium demand scenarios and can be problematic for high demand levels (*31*). Additionally, pedestrian movements are strictly separated from vehicle movements in the AIM scenario, leading to further capacity reductions. Therefore, advanced control algorithms shall be tested in the future.

Evaluation of Pedestrian Waiting Times

To assess the pedestrian level of service, the difference between the time a pedestrian p arrives at a crosswalk c and the time that a pedestrian green light is shown at c is measured as the pedestrian waiting time $wait(p, c)$. If p wants to pass several crosswalks, then waiting times are added, that is, $wait(p) = \sum_c wait(p, c)$. Similar to the average delay for vehicles, the average pedestrian waiting time is calculated as

$$\overline{wait(P)} = \frac{1}{|P|}\sum_{p \in P} wait(p) \tag{6}$$

where P is the set of all pedestrians that cross the intersection during a simulated period of time.

Average pedestrian waiting times for each demand scenario are presented in Figure 6. Figure 6*a* shows that average waiting times are comparable for the AIM and the AT scenarios. The AT scenarios show a higher

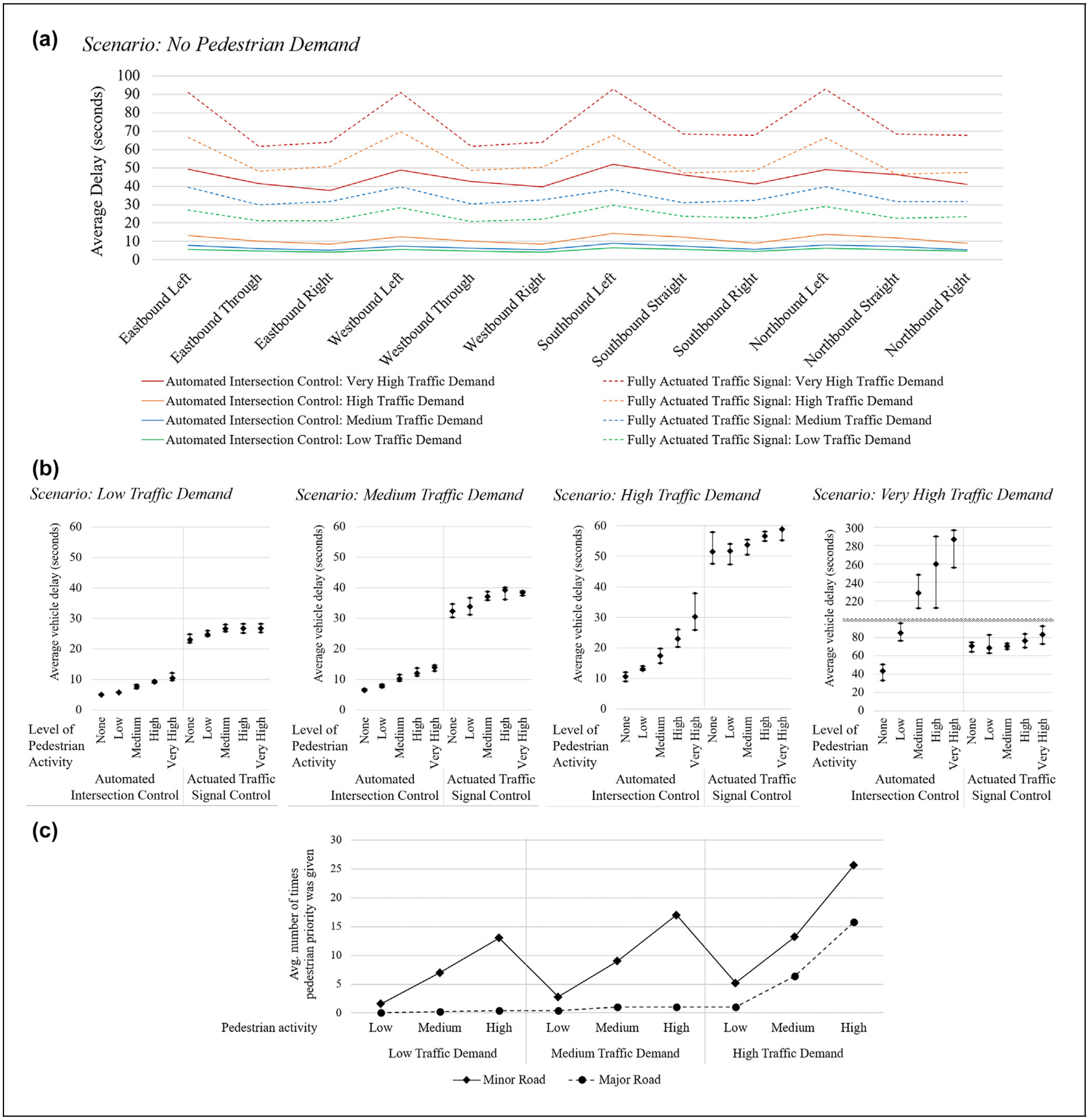

Figure 5. Vehicle delays and number of times pedestrian priority was granted for different scenarios: (*a*) average vehicle delay for the different control strategies assuming no pedestrian demand, (*b*) average vehicle delay depending on the combination of traffic demand, control strategy, and pedestrian activity, and (*c*) average number of times that pedestrian priority was given depending on traffic demand and pedestrian activity.

stochasticity, because the control is not responsive to pedestrian demand. Since the number of pedestrians in the scenario is low, the waiting time of a single pedestrian has a high impact on $\overline{wait(P)}$. The longer cycle times in the scenario with high traffic demand increase this effect. Interestingly, pedestrian waiting times are lower for the AIM scenario with very high vehicle demand. This results from pedestrian priority being given for almost every pedestrian. Additionally, if pedestrian activity is high, there is often another pedestrian already waiting.

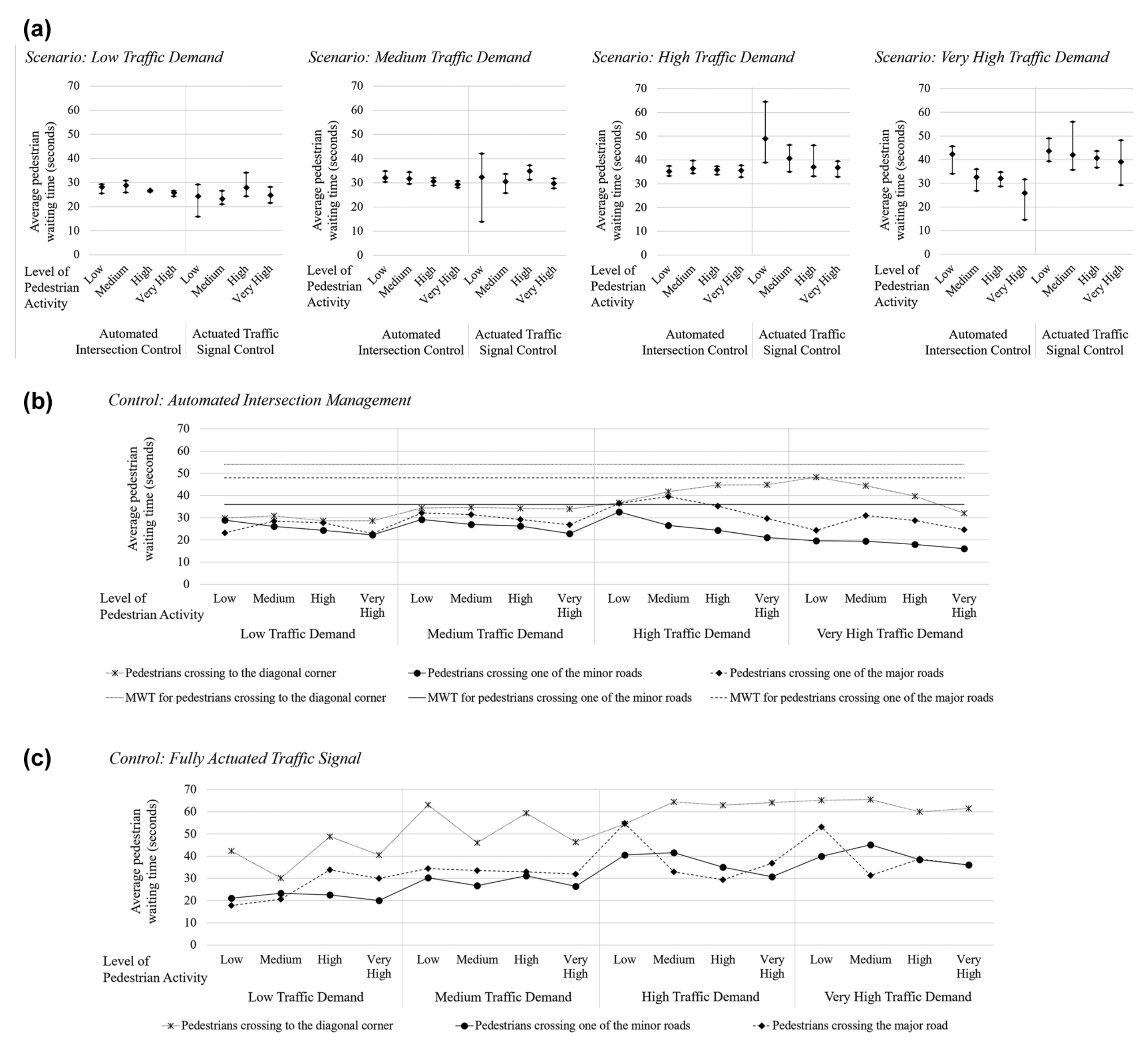

Figure 6. Pedestrian waiting times: (*a*) average pedestrian waiting times depending on the combination of traffic demand, control strategy, and pedestrian activity, (*b*) average pedestrian waiting times in the AIM scenario depending on the traffic demand and pedestrian activity, and (*c*) average pedestrian waiting time in the AT scenario depending on the traffic demand and pedestrian activity.
Note: AIM = autonomous intersection management; AT scenario = fully actuated traffic signal control scenario; MWT = maximum waiting time.

Figure 6, *b* and *c*, present the average pedestrian waiting times depending on the origin–destination relation of pedestrians. As expected, waiting times for pedestrians who cross to the diagonal corner of the intersection are longer than waiting times for pedestrians who cross one of the streets. Even though average waiting times are similar for both control scenarios, it can be seen that maximum waiting times are significantly shorter in the AIM scenario, sometimes even below the average waiting time in the AT scenario.

Conclusion and Outlook

In this paper, a novel strategy for fully integrating pedestrians into AIM is presented. It consists of an FCFS control for vehicles in combination with an on-demand traffic signal for pedestrians. The core of the control is a defined maximum pedestrian waiting time that must not be exceeded. Pedestrian phases in the AIM scenario are fully protected thus providing a high level of pedestrian safety. The proposed intersection control was described, implemented, and tested for a set of scenarios considering several levels of traffic demand and pedestrian activity. Vehicle delays and pedestrian waiting times were evaluated and compared with a fully actuated traffic signal. The presented AIM performed significantly better than the AT for low, medium, and high demand scenarios. However, including pedestrian activities into the AIM control with very high vehicle demand led to very long delays.

To further improve the performance of the proposed AIM, the reservation strategy will be changed from a modified FCFS control to a more sophisticated strategy in the future. In fact, an optimization problem can be considered that can be formulated as

$$\min\left(\sum_{v \in V} delay(v) \cdot w_v + \sum_{p \in P} wait(p) \cdot w_p\right) \qquad (7)$$

where w_v is a weight assigned to vehicle v and w_p is a weight assigned to pedestrian p. These weights can depend on the occupancy of vehicle v, for example, or on the local policy in relation to pedestrian priority, and can be changed dynamically according to the current situation. The problem is subject to several constraints including safety gaps and physical restrictions. It could possibly be modeled as a mixed-integer linear program similar to the one presented by Fayazi and Vahidi (*32*). The next steps for the authors will also include considering bicyclists at the intersection zone. Bicyclists can already be considered at the pedestrian crosswalk in the current control. However, in the future, they are going to be considered separately to avoid stops for bicyclists.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Tanja Niels, Klaus Bogenberger, Nikola Mitrovic, Aleksandar Stevanovic; data collection: Tanja Niels, Nemanja Dobrota; analysis and interpretation of results: Tanja Niels, Nikola Mitrovic; draft manuscript preparation: Tanja Niels, Klaus Bogenberger, Aleksandar Stevanovic, Robert L. Bertini. All authors reviewed the results and approved the final version of the manuscript.

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