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Design and Evaluation of V2X-Based Dynamic Bus Lanes

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ABSTRACT In mixed traffic, the popularity of public transport (PT) is still affected by relatively low operating speeds compared to private vehicles. To overcome this, PT priority measures have been proposed and adopted extensively. However, existing solutions such as exclusive bus lanes or traffic signal priorities are often limited in terms of available road space or large-scale feasibility. In this paper, we propose a Vehicle-to-Vehicle/Infrastructure (V2X)-based dynamic PT priority concept in mixed traffic called Virtual Right of Way (VROW). Private vehicles in front of a PT vehicle make spaces through collaborative lane changes within a dynamic clearing distance computed based on the current traffic situation. This allows a more efficient allocation of road space while still maintaining a high level of PT priority. In this paper, we evaluate the potential traffic impacts of VROW on both PT and private vehicles by conducting microscopic traffic simulations within a small urban network and a highway scenario. Comparisons with mixed traffic and other existing bus lane priority strategies, in terms of operation and safety concerns, are analyzed and highlighted. Simulation results show that VROW improves the PT operational performance with only a marginal influence on private vehicles measured by their average travel time and the number of lane changes.

INDEX TERMS Dynamic bus lane, microscopic traffic simulation, traffic impact analysis, V2X.

I. INTRODUCTION

To increase the attractiveness of public transport (PT), especially in urban mixed-traffic, prioritization measures that favor PT operations are required to achieve a significant improvement of travel times and reliability [1], [2]. Multiple prioritization measures have been studied and widely adopted [3]–[6], for instance, traffic signal priorities, exclusive bus lanes, parking controls at bus stops, queue jump lanes, etc. Most existing measures have limitations in their applicability. For example, exclusive bus lanes are considered as an inefficient allocation of road space when the bus volume is low, and they limit the number of accessible lanes for private vehicles if they are converted from general traffic lanes [2]. To overcome the limitations of exclusive bus lanes, concepts of intermittent bus lanes [7] and bus lanes with intermittent priority [8] were proposed to provide a fixed-length lane section for bus priority when a bus is present. For these systems to perform well, a certain level of traffic signal priorities should be implemented to allow the queue in front of the traffic signal to clear before the bus arrives. These systems additionally do not consider the current traffic situation or road geometry which hinders large-scale implementation.

Even with existing prioritization measures, it is quite common for PT vehicles to be unable to benefit fully, when the travel distance and the number of intersections increase. The primary reason is the challenges involved in such large-scale deployment of PT prioritization in mixed traffic, including the constraints from road networks, conflicting priority requests, as well as unfavorable impacts on other vehicles. In the past decade, PT prioritization techniques have not evolved much and most of them focus on providing benefits for either a smaller segment of the PT route or only at certain times. With technical advancements in traffic management and operation, we believe an integrated PT priority solution without a significant negative impact on other traffic is now feasible.

In this study, we develop, implement, and evaluate a V2X-based dynamic bus priority concept called Virtual Right

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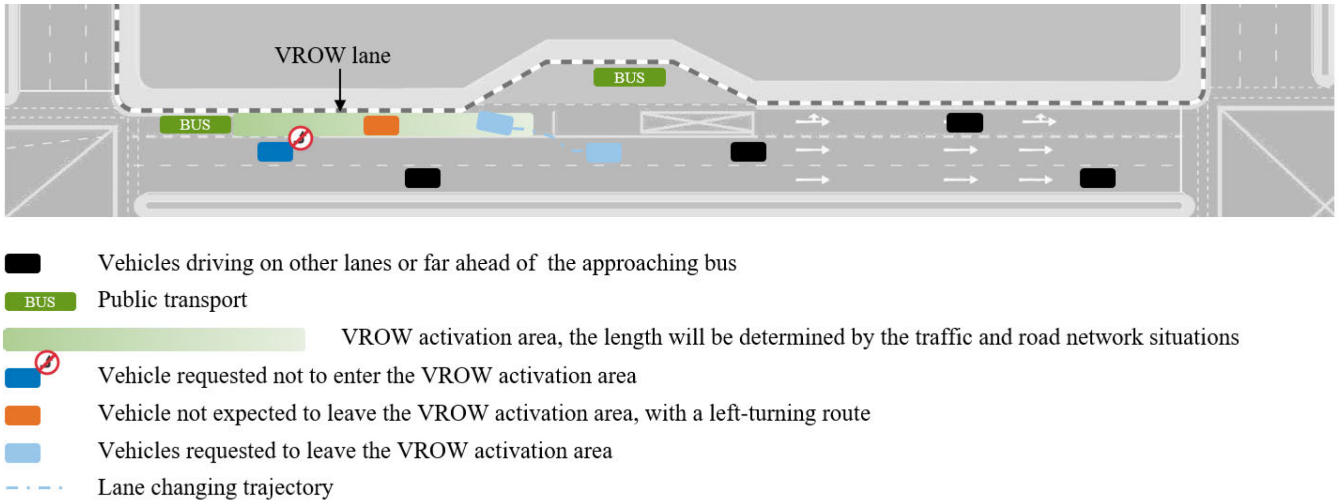


FIGURE 1. Illustration of the envisioned dynamic bus lane concept: An approaching bus requests other vehicles to provide a dynamic clearing distance in front of it (VROW activation area), based on the current traffic and road situations. Vehicles driving on other lanes or far ahead of the approaching bus are not influenced by the VROW system. The vehicle in dark blue is requested not to enter the VROW activation area, indicated with a forbidden left-turn sign. The vehicle not expected to leave the lane (colored in orange) is a left turner that can share the VROW lane even when a bus is present. Vehicles marked with a lane-changing trajectory are requested to leave the VROW activation area.

of Way (VROW). The concept is illustrated in Fig. 1. Based on bus demands, the road space is dynamically shared by both buses and other vehicles. Using V2X techniques, the bus priority request can be transmitted to nearby vehicles. According to the current traffic and road network conditions, vehicles in the vicinity would individually provide a dynamic clearing distance in front of buses through collaborative lane changes. By doing so, buses obtain a Virtual Right of Way when it is sensed by the other vehicles. Other vehicles on the adjacent lane of an approaching bus are restricted from changing to the 'VROW lane', as they may interfere with the bus operation. Upstream vehicles are not directly influenced by the VROW requests. Downstream vehicles with a turning route choice or queuing near intersections, can continue to use the reserved VROW lane. When a bus stops to serve passengers, all lanes are accessible to other vehicles because no priority is requested. Once it is about to exit the stop, other vehicles are informed in advance that VROW is reactivated.

Using V2X communication, VROW can provide adequate bus priority along the route based on current traffic situations, without requiring any signal timing changes. Meanwhile, multiple buses can also benefit from the other buses' priority requests and share the pre-reserved VROW lane. Further, it has a wider application range and reduces the potential negative impacts on other vehicles when compared to other existing prioritization measures.

The key contributions of this paper are:

- A novel dynamic prioritization technique for PT based on V2X communication is developed and implemented, taking into consideration heterogeneous traffic flows, traffic signals, and bus dwelling.
- Evaluation of the proposed technique and comparisons with mixed traffic and other existing bus lane priority strategies are conducted using microscopic traffic simulations. Two case studies are carried out to explore the performance of VROW under representative scenarios.
- The potential operational performance and safety concerns of both PT and private vehicles are analyzed, and the potential application areas of VROW are introduced.

The remainder of this paper is organized as follows: Section II reviews the literature and field tests in relevant areas. Section III describes the proposed concept, methodology, and implementation details. Section IV analyzes and evaluates the results and compares VROW with mixed traffic and other existing bus lane priority strategies. Finally, Section V concludes the findings and describes future research directions.

II. RELATED WORKS

Prioritization measures to protect buses from mixed-traffic congestion, such as traffic signal priorities or exclusive bus lanes, usually can contribute to reducing the travel time differences between PT and private vehicles and, thereby, make PT more attractive and fuel-efficient [9], [10]. Unfortunately, it is a challenging task to deploy these measures at a network level without appropriate justifications, due to their potential negative impacts on other traffic [11]. While in heavy traffic, the effectiveness of priority measures is limited as traffic signals or bus lanes have to account for the increased traffic volume to avoid worsening traffic conditions [12].

Exclusive bus lanes have been widely used and have effectively improved bus operations around the world [6], [13]–[15]. In practice, it is not always possible to provide such permanent lanes, as for example curb-side bus lanes would block vehicles from accessing entrances and exits along the roadside [16], [17]. Besides, a set-back length is

TABLE 1. Comparison of different bus lane priority strategies.

Type	Advantages	Limitations
Exclusive bus lane (EBL) [6], [13]–[15]	Buses have dedicated access to the exclusive bus lane.	Fewer accessible lanes for private vehicles; inefficient road space allocation when the bus volume is low; set-back length limits bus benefits.
Intermittent bus lane (IBL) [7], [23]–[27]	Buses and private vehicles share the bus lane; access for private vehicles to road-side premises is not affected.	Depends on traffic signal priority to clear the queue in front of the bus; fixed active segment ahead of the bus regardless of traffic situations.
Bus lanes with intermittent priority (BLIP) [2], [8], [12], [28]	Buses and private vehicles share the bus lane; less dependent on traffic signal priority to clear the queue.	Fixed active segments ahead of the bus regardless of the traffic situations; it is assumed that traffic flow is homogeneous with little turning ratios; no details about bus dwelling in stops/bays.
Virtual Right of Way (This paper)	Bus and private vehicles share the bus lane; access for private vehicles to road-side premises is not affected; independent of traffic signal priority; heterogeneous traffic flow, bus dwelling and signalized intersections are considered; dynamic clearing distance adapts to road and traffic situations, achieving higher road-use efficiency.	Depends on V2X communication; requires a 100% penetration rate of V2X technology.

usually provided for private vehicles at intersections, where the exclusive bus lane stops short of the intersections allowing private vehicles to utilize the full carriageway width so that the throughput capacity is maintained [18]. As a result, this diminishes the bus benefits over the route [18], [19]. Additionally, deploying exclusive bus lanes is considered inefficient as it leads to a reduced road capacity when bus volumes are low [16], [17], [20]–[22]. In most sections of an urban bus network, even if the bus volume does not reach the justification threshold of deploying exclusive bus lanes, buses may still require priorities to maintain a higher operational speed in congested scenarios.

To mitigate the drawbacks of exclusive bus lanes, the concept of intermittent bus lane was presented in [7], which changes the dedicated usage of a fixed-length lane section according to the presence of buses. When a bus is approaching, the status of that lane is intermittently changed to an exclusive bus lane. The intermittent bus lane turns to a normal lane once the bus moves out of it. Private vehicles on other lanes are restricted from accessing the intermittent bus lane, but vehicles (ahead of the bus) that are already on this lane can remain or change to other lanes as they wish. This concept strongly depends on the implementation of traffic signal priorities in order to clear downstream queues in front of the buses. Several field tests and permanent deployments have been conducted in Lisbon [23], Melbourne [24], Bologna [25], and Lyon [26]. There is a high variance in the results of similar projects, which can be explained by the differences in traffic conditions and volumes [27]. These papers declared that the impact on private traffic is trivial when bus volumes are low, yet no further details are given. The previous studies often ignored that it is also necessary to determine an optimal combination of private traffic volume, frequency of PT operation, and length of the deployment segment [27].

A concept of bus lanes with intermittent priority is introduced in [8], which does not merely forbid the vehicles from entering the intermittent bus lane, but also requires the vehicles that have entered the bus lane to move out. It can be seen as a moving bus lane segment of static length in front of the bus where private vehicles are not allowed. This addition to the previous intermittent bus lane system reduces the dependence on traffic signal priorities, which is to avoid the formation of queues in front of the buses [2].

However, a homogeneous traffic flow with little turning traffic is assumed, and the impact on private traffic is not studied [12].

Table 1 provides a summary of the related work along with their respective advantages and limitations. In this paper, we aim to overcome these limitations and present a V2X-based dynamic bus priority solution in which private vehicles provide a dynamic clearing distance in front of the bus without relying on traffic signal priorities.

III. METHODOLOGY

In this article, we design a V2X-based dynamic bus lane concept (VROW). Under VROW operation, buses are given a spatial advantage when needed under the assumption of full collaboration from private vehicles as well as the availability of V2X communication. This is realized by requesting the private vehicles to provide a dynamic clearing distance in front of the approaching buses. Private vehicles individually determine their clearing distances according to the real-time traffic situation and their route choices.

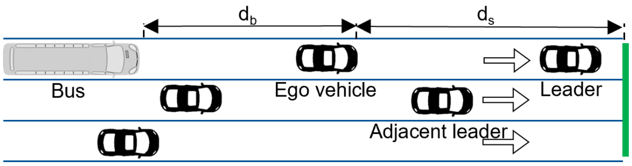


FIGURE 2. Illustration of relative positions of vehicles.

A. SYSTEM DESIGN

In urban mixed-traffic scenarios, bus operation is usually influenced by private traffic, bus stop spacing, traffic signal timing, and dwell times [29], [30]. As stated in [31], traffic interference results in a significant amount of delay for buses, which in turn affects the competitiveness of buses compared to private vehicles. To reduce interference from private vehicles, VROW requires them to make way for the approaching bus. Such collaborative lane changing behavior from private vehicles is expected to improve the operational performance of buses and reduce the speed differences between private vehicles and buses. Each vehicle shall follow a common lane-change rule set which considers both speed and position of itself and the prioritized bus, while also taking into account the traffic signal timings and bus dwell times.

The inputs for collaborative lane changing rules of the individual ego vehicle include (see Fig. 2 for reference):

1) Speed-related:
    - v_b the ideal operating speed of the approaching bus
    - v_c the current speed of the individual ego vehicle in front of the approaching bus
2) Gap-related:
    - d_s the distance gap between the individual ego vehicle and the next signal stop line
    - d_b the distance gap between the individual ego vehicle and the approaching bus
    - t_f the time gap between the individual ego vehicle and its leader on the same lane
    - t_f^{Ad} the time gap between the individual ego vehicle and its leader on the adjacent lane
3) Signal-related:
    - t_g the residual time of green phase
    - t_r the residual time of red phase

Upon reception of a VROW priority request, each vehicle calculates an "ideal" time gap between itself and an approaching bus to determine if it needs to make way for the bus. The ideal time gap H_{id} is the ratio of the distance between the individual vehicle and the approaching bus and the difference between the current speed of the individual vehicle and ideal operating speed of the bus, as in:

$$H_{id} = \frac{d_b}{(v_b - v_c)} \tag{1}$$

This ideal time gap between an approaching bus assuming its target ideal speed and the individual vehicle is further compared to t_f and the individual vehicle's time to pass the next intersection, t_{SG}. If an approaching bus with the ideal operating speed can use less time than the individual vehicle before it passes the next intersection or catches up the leading vehicle on the same lane (this means the individual vehicle must slow down to avoid collision), the vehicle has to leave the VROW lane. This can be expressed as:

$$H_{id} < min(t_f, t_{SG}) \tag{2}$$

The time for an individual vehicle to pass the next intersection can be denoted as:

$$t_{SG} = \frac{d_s}{v_c} \tag{3}$$

This is also related to the signal phase and timing of the next intersection, for instance, when the vehicle arrives at the intersection within a red phase, the residual time of red phase shall be incremented. This is captured in:

$$t_{SG} = \begin{cases} \dfrac{d_s}{v_c} & \text{within green phase,} \\ \dfrac{d_s}{v_c} + t_r & \text{otherwise.} \end{cases} \tag{4}$$

The real-time nature of the VROW operation, which entails reassessing the lane change decision at regular time intervals, mitigates the impact of downstream vehicles not traveling at constant speeds or queues at traffic signals not clearing fast enough.

Additionally, certain vehicles on adjacent lanes are restricted from entering the VROW lane, due to the potential of interfering with the bus operation. This is determined by the vehicle route choice and real-time traffic situation. If a vehicle is currently in a queue or it has to use the VROW lane to make a turn according to its route, it is allowed to use the VROW lane. To make efficient use of the road capacity, vehicles not interfering with the bus operation are also allowed to use the VROW lane. Whether or not a vehicle is interfering is determined similar to equation (2), in consideration of a potential lane changing duration, which is represented as:

$$H_{id} > max\left(t_f^{Ad}, t_{SG}\right) + D_{LC} \tag{5}$$

where D_{LC} is the potential lane-change duration of the vehicle. In other cases, the vehicle on the adjacent lane shall not enter the VROW lane.

A detailed flowchart of the overall system is shown in Fig. 3. All private vehicles in the network periodically check if there is an approaching bus from behind, with a sensing distance limit of 250 m. This parameter is set according to the expected wireless communication range of V2X systems [32]–[34]. Once a vehicle detects an approaching bus on its current or adjacent lane, it determines whether it affects the ideal bus operation according to equations (1), (2), (4), and (5). Private vehicles that are currently queuing, have no available adjacent gap to change lane, or need to occupy the VROW lane due to their route,

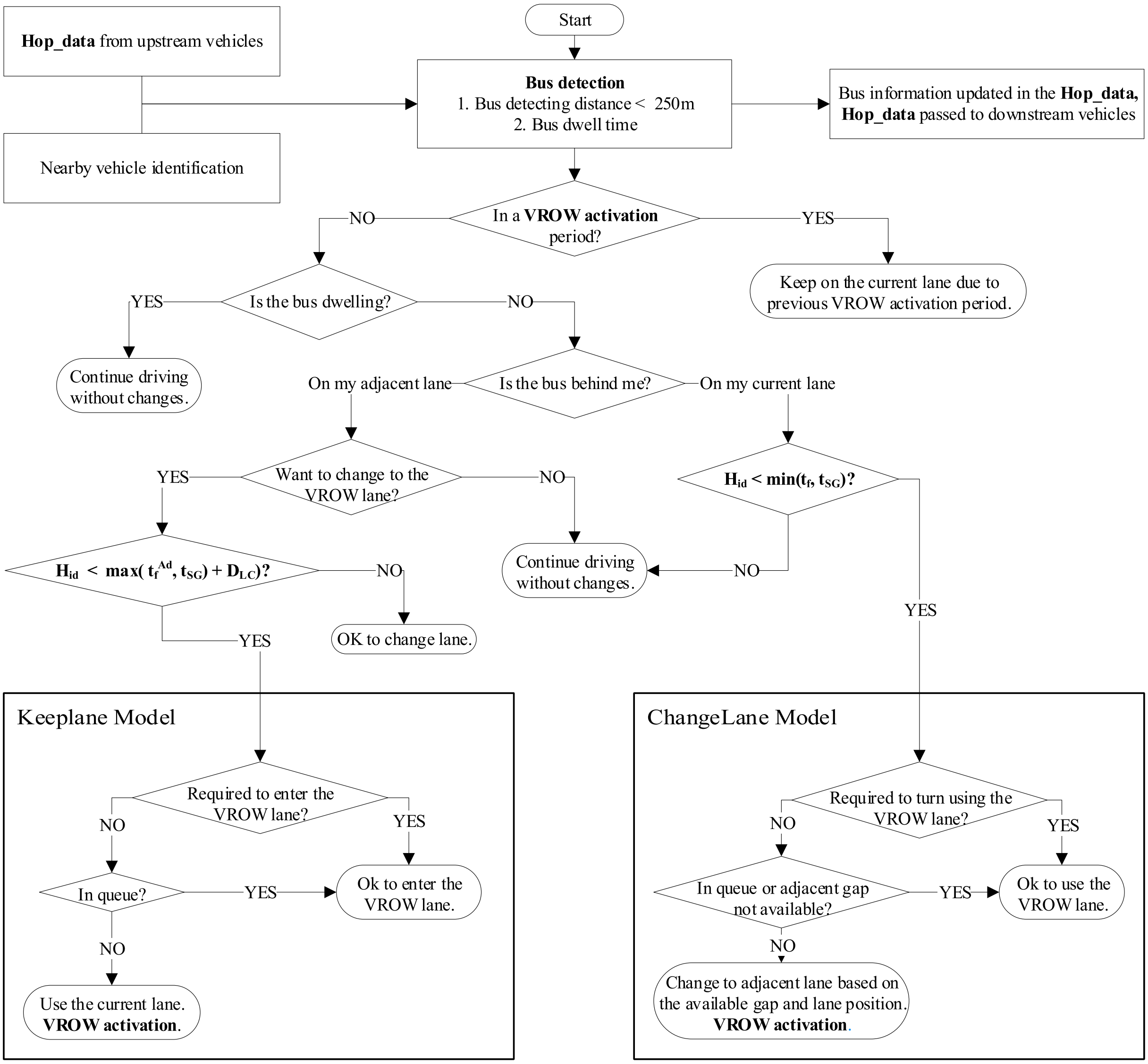


FIGURE 3. A flowchart of the V2X-based dynamic bus lane concept from the view of a private vehicle.

may still use the VROW lane. To lower the safety risk induced by multiple lane changes in a short time interval, each vehicle can refuse a VROW priority request if the time interval between two consecutive requests is within a limit, i.e., the VROW activation period. To capture the data from V2X communication, a hop_data structure is created to store the information from approaching buses in terms of relative distance, current lane, and dwell time. This hop_data is transmitted by the approaching bus to the downstream vehicles.

B. COMMUNICATION

The VROW system relies on informing vehicles about the presence of a bus and the need to change lanes to make way for an approaching public transport vehicle. For the decision making process to be done locally at each vehicle, it needs the position and velocity of the bus, access to its own parameters such as speed and position, and a common rule set as described in Section III-A. The latter two can be achieved without communication by use of an on-board unit, while the former requires a method of information exchange and subsequently signaling to the driver.

In theory, this could be achieved via variable message signs, although this approach would be challenging as it either requires separate information for each passing vehicle or requires the drivers to determine whether they have to change lanes based on the information displayed. Using V2X communication seems to be the logical solution, however, requires a 100% penetration rate as unequipped vehicles would be unable to receive the V2X message and therefore not change lanes. It is predicted that by the end of 2022, V2X will account for a market worth \$1.2 Billion, with an installed base of nearly 6 Million V2X-equipped vehicles worldwide [35], however, this does not guarantee a 100% penetration rate. Upcoming systems such ERP 2 [36] in Singapore where each vehicle is mandated to have a communication-enabled on-board unit would ensure such a penetration rate and therefore allow a V2X-based VROW to be installed.

Requirements in terms of latency, bandwidth, and robustness determine which underlying technology should be used. When it comes to latency, VROW does not have strict requirements such as safety applications where the expected latency boundaries are much lower [37]. Compared to the reaction time and decision making of the driver, we expect the added latency caused by the communication to be negligible, even if it was as high as 1 or 2 seconds. In terms of bandwidth, VROW does not require noteworthy additional resources as the information required by the other vehicles is largely already part of periodic safety messages (BSMs in North America, CAMs in Europe). The required additional fields include flags to indicate whether the bus is dwelling and whether VROW is active; everything else is derived by the respective vehicles locally, either through sensors or through cooperative awareness enabled by the underlying communication system [38]. The most important requirement is robustness with respect to packet success rates as VROW relies on all relevant vehicles within a certain distance in front of the bus to be informed. For such short ranges of up to 250 m, it is a reasonable assumption that a high packet success rate can be achieved. If this was not the case, then the underlying communication system could also not support any safety applications, defying the main purpose of V2X communication.

From the requirements, we conclude that VROW is not limited to a specific communication technology but could be realized by Dedicated Short Range Communication (DSRC), i.e. usually based on IEEE 802.11p or IEEE 802.11bd [39], by cellular-based V2X communication [40], i.e., 4G D2D or 5G NR-V2X, or even on a completely cellular solution. If DSRC is used, multi-hop communication is already supported by the standards and approaches such as geographic routing, which can be utilized to inform all vehicles using broadcast mechanisms [41]. The prioritized public transport vehicle periodically broadcasts its state and vehicles receiving this information forward it to ensure all vehicles in the target area receive the information. The same principle can be applied for any direct device-2-device (D2D) communication. When communication involves a third entity, for instance, a cellular base station or a road-side unit, this entity itself can determine which vehicles need to be informed as it normally maintains a list of all connected devices. The range of these base stations is usually higher than the requirements of the envisioned VROW system. In summary, we conclude that VROW does not require a specific communication technology and that there exist a multitude of solutions to support the communication requirements for VROW as long as it can be ensured that all vehicles in the target area are equipped with that technology. In this paper, we are assuming information about approaching buses to be broadcast to all vehicles in the vicinity.

TABLE 2. Simulation parameters of highway case study.

Parameter	Value
Simulation period	3900 s (300 s for warming up)
Simulation resolution	2 time steps per simulation second
Target traffic volumes	4200, 5300, 6400 veh/h
Bus volume	90 veh/h
Number of repetitions	5

IV. RESULTS AND ANALYSIS

We implemented a range of bus priority strategies including VROW in the microscopic traffic simulator PTV VISSIM [42]. We evaluated two simulation scenarios, a synthetic highway scenario and a real urban road network, calibrated to real traffic volume and speeds. The goal of the first experiment is to carry out a general comparison of the performance of VROW with other bus lane priority strategies in an artificial scenario, while the second experiment gives an indication of the actual traffic speeds to be expected in a real two-lane setting. Each simulation lasts for 3900 seconds with a warm-up period of 300 seconds and a simulation resolution of two time steps per second. The results are reported based on a significance level of p-value < 0.05. Multiple runs with random seeds are conducted to obtain statistically reliable results, considering the stochastic nature of the used simulation models.

A. HIGHWAY CASE STUDY

We simulated a 1 km straight three-lane road under saturated traffic volumes, without influences from traffic signals and bus stops/bays. We compare VROW to four other strategies: Mixed-traffic (buses and cars share the lane), Exclusive Bus Lanes (EBL), Intermittent Bus Lanes (IBL) [7], and Bus Lanes with Intermittent Priority using a rolling bus segment of 250 m (BLIP250) [8]. Since the performance of bus priority lanes is particularly interesting for higher traffic volumes, we evaluate three different levels, ranging from 4200 to 6400 veh/h in steps of 1100 veh/h (note that a traffic volume of 2000 veh/h/lane is considered ‘saturated’ in VISSIM). The bus volume is set to a constant 90 veh/h. A summary of simulation parameters is shown in Table 2.

First, we measured the achieved traffic throughput given different target traffic volumes. The results are visualized in Fig. 4. For the lowest target volume of 4200 veh/h, nearly all vehicles in the simulation could finish their journey through the highway segment. This changed when the volume increased to 5300 veh/h, as the road capacity with the EBL strategy was not enough for the generated traffic. For the highest traffic generation rate, we observe that the mixed strategy performs the best, followed by IBL and VROW. IBL allows a higher throughput as it does not require vehicles already on the bus lane to change. As expected, BLIP250 and VROW perform similarly, with VROW benefiting from the

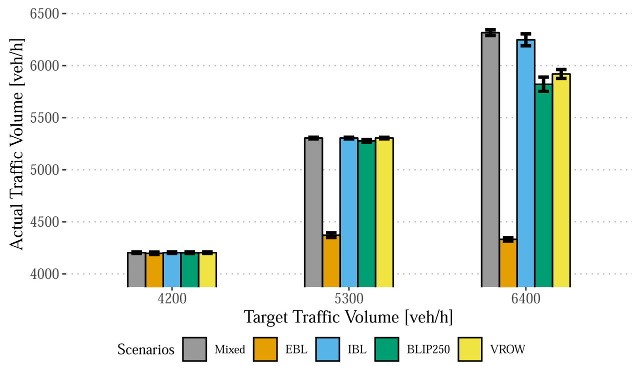
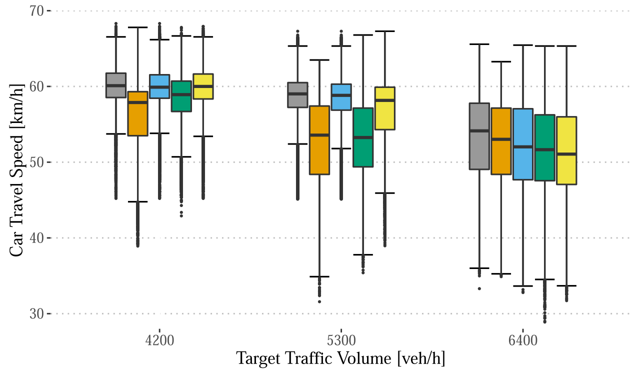
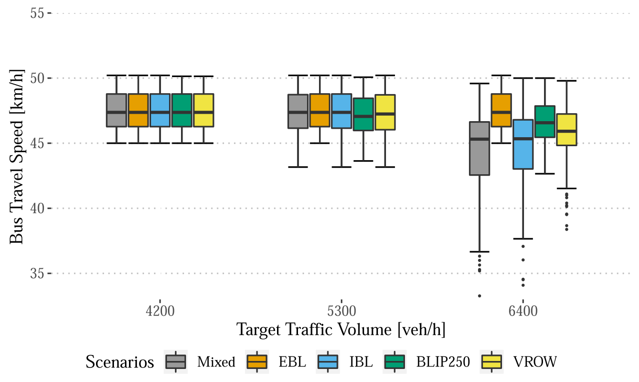


FIGURE 4. A summary of private vehicle counts under different target traffic volumes in the highway case study. Error bars show the standard deviation of the various simulation runs.



(a) Car travel speeds



(b) Bus travel speeds

FIGURE 5. A summary of car and bus travel speeds under different target traffic volumes.

dynamic size of the activation area. These results need to be kept in mind when discussing the next findings, as only average speeds for vehicles, that were able to fully traverse the highway segment, were taken into consideration.

Next, we evaluated the travel speeds of cars and buses under different traffic volumes, presented in Fig. 5. In general, cars and buses experience reduced speeds as the traffic volume increases. Evaluating only the travel speeds of affected private vehicles (Fig. 5a), we observe that at target volume of 4200 veh/h, the car speeds of all strategies are similar with the exception of the EBL strategy, where the blocked lane for private traffic already shows a negative impact on the travel speed. The situation changes when traffic volume further increases, as now both BLIP250 and EBL have a substantial effect on the car travel speeds (please note that the actual traffic volume was considerably lower for EBL as discussed above). The VROW strategy performed slightly worse when compared to IBL or mixed traffic, which was expected, as vehicles changing lanes cause a disruption in traffic flow. Lastly, with a traffic volume way above the road capacity, all strategies exhibited similar car travel speeds, however, as discussed above, the throughput was different.

Looking at the travel speeds of buses (Fig. 5b), we note that the differences between the strategies become evident in a saturated scenario where both IBL and the mixed strategy performed worst. This can be seen as the trade-off for achieving higher private vehicle speeds. EBL and BLIP250 performed best as they are more conservative in reserving road space for the buses. With a slightly lower bus speed, VROW achieved its design goal of offering a good balance between bus travel speed and impact on private traffic.

B. URBAN CASE STUDY

Since the synthetic scenario can only give limited insights into the performance of VROW that can be expected on a real network, we selected an area in Singapore to be modeled accurately in the simulation environment, shown in Fig. 6. The area has four signalized intersections with four bus services in operation. The main corridor is a minor arterial two-lane two-way road with a central median extending to three lanes at intersections. It is about 1260 m long with three bus stops/bays per direction. The traffic volume during morning and evening peak hours is medium with approximately 1000 veh/h per link per direction. Currently, this area has no bus priority strategies in operation, due to the low bus volume of 35-45 veh/h/dir and the present road space restrictions. The traffic counts and signal timings were collected from inductive loop detectors and the SCATS system [43]. We used traffic videos and the AI-based analysis tool DatafromSky [44] to further calibrate vehicle counts and speed, including vehicle types such as buses, private cars, motorcycles, and heavy goods vehicles (HGV). We also conducted a bus survey to collect dwell times and travel speeds of four bus services at different times of the day.

We compared the performance of the currently deployed bus strategy (i.e., mixed) with VROW in the morning and evening peak hours. To allow for easy comparison, all parameters such as traffic volume, vehicle speed, bus dwell time, etc. are assumed to be the same for both strategies.

In Section III-A we described how the clearing distance (or the VROW activation area) is determined by each vehicle based on its difference of current speed and position compared to the approaching bus. In Fig. 7 we show a histogram over the derived clearing distances in the simulation. The results show that vehicles in the a.m. scenario usually

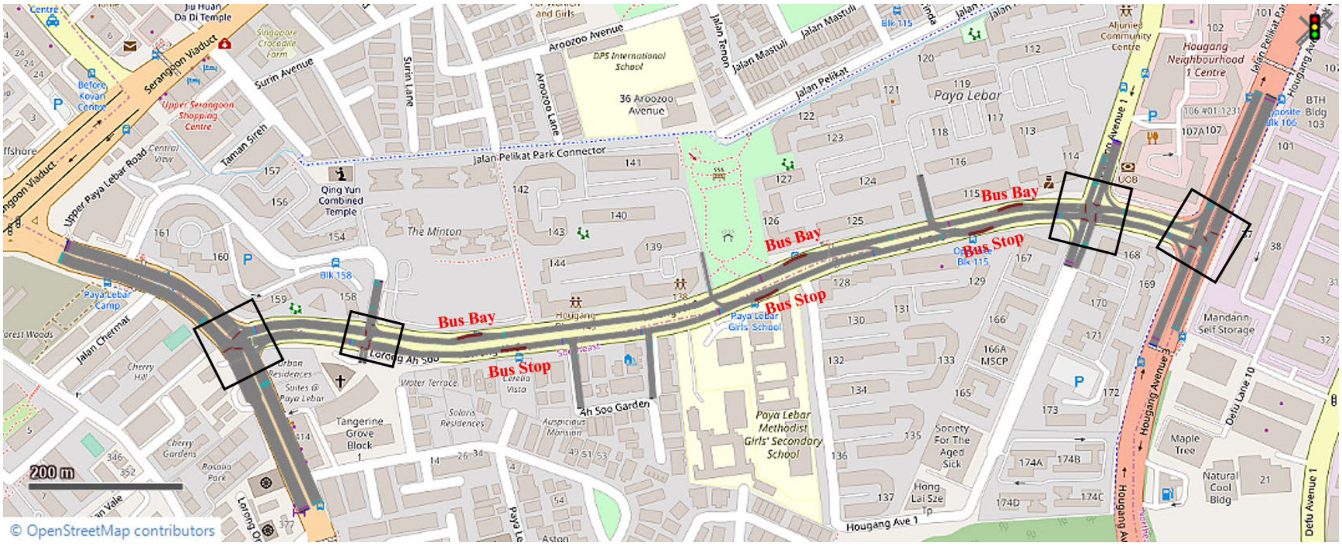


FIGURE 6. Illustration of the study area: The four signalized intersections are indicated with black rectangles. The bus stops/bays are indicated with red rectangles and texts along the roadside.

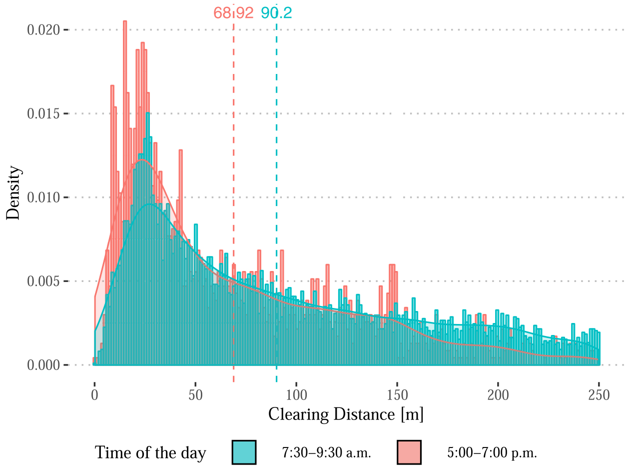


FIGURE 7. Histogram and density plot of private vehicles' dynamic clearing distance at different times of the day: When an individual vehicle starts to react to the VROW request, the clearing distance is measured between itself and the approaching bus. The vertical lines with value display the average clearing distances at different times of the day.

TABLE 3. Comparison of average travel time.

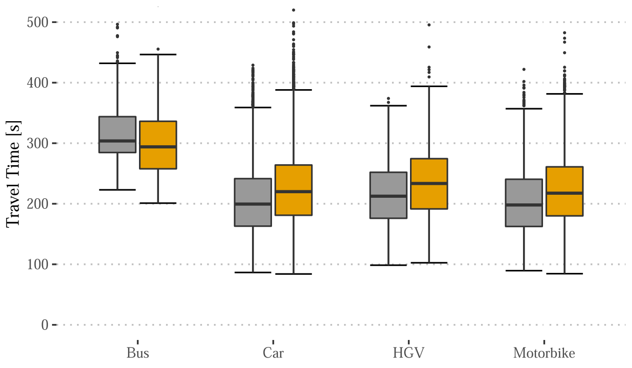
VROW-Mixed		Mean difference [s]
a.m.	Bus	-15.36 ***
	Car	+20.95 ***
	HGV	+22.84 ***
	Motorbike	+19.26 ***
p.m.	Bus	-18.39 ***
	Car	+15.21 ***
	HGV	+18.09 ***
	Motorbike	+11.45 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

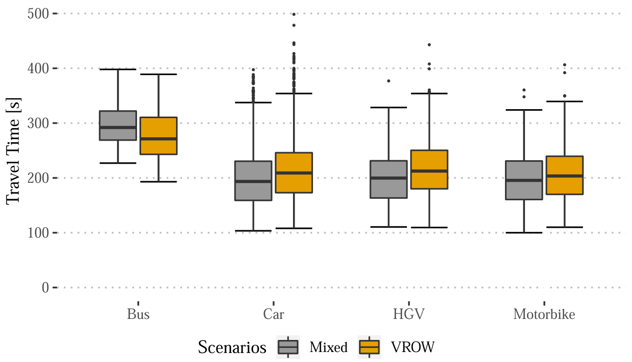
performed their collaborative lane changes earlier than those in the p.m. scenario, with average clearing distances of 90.20 m and 68.92 m, respectively. This is due to higher traffic volumes in the morning, which requires longer clearing distances so the operation of the bus is not affected. In the evening peak hour, where traffic volumes were lower, we observed shorter clearing distances as less time was required to clear queues at stop lines.

To understand the impact of VROW introduction on both bus and other vehicles, we evaluated travel times through the scenario for the mixed and VROW strategy. Our findings are shown in Table 3 and Fig. 8. We observed that the bus travel times are lower when VROW is implemented with a recorded travel time reduction of 15.36-18.39 s. Please note that this improvement is achieved without relying on traffic signal priorities or exclusive bus lanes, but on a 100% penetration rate of V2X technology. This means that there is no impact on cross traffic, something commonly associated with the implementation of bus signal priorities. We expect VROW to provide a more significant enhancement when there are longer distances between bus stops. As expected, private vehicles took slightly longer to traverse through the scenario when VROW was enabled. We recorded a travel time increase of 11.45–22.84 s with a significance level of p-value less than 2e-16. However, assuming an average occupancy per private vehicle of 1.7 in the 1100 affected vehicles, VROW would require an average ridership of 63 passengers in the passing 40 buses to achieve an overall improvement of travel time per individual in the a.m. setting (and only 12 passengers for the p.m. setting). Bus utilization is usually higher during peak hours; an average number of 90 passengers per bus would yield an accumulated travel time reduction of 4.5 hours (and 17 hours for p.m.).

The VROW system moves the travel times of buses and private vehicles closer together, from 107.98 s to 71.60 s and 98.82 s to 65.52 s, for a.m. and p.m. respectively. We expect



(a) 7:30-9:30 a.m.



(b) 5:00-7:00 p.m.

FIGURE 8. **A summary of travel time changes in the morning and evening peak hours. Lower is better.**

that with higher traffic volumes (i.e., those similar to the highway study), VROW will bring more benefits to buses, further reducing the differences of travel times between buses and private vehicles. This can contribute to increasing the attractiveness of bus transport and support a potential modal shift towards the PT system [45], [46].

We observe that VROW offers more relative bus travel time reduction compared to mixed operation in the less congested p.m. scenario, mainly caused by the shorter clearing distances required from other vehicles (cf. Fig. 7). For other types of vehicles, the difference in travel times is smaller in the p.m. setting, showing that VROW is able to achieve a good balance for moderate traffic volumes.

The major safety concern of dynamic bus lanes is that they introduce frequent lane changes that may negatively affect traffic safety. We therefore investigate for each vehicle group the average number of lane change per vehicle for the mixed lane and VROW strategies. The recorded lane changes are taken from all vehicles passing through the 1.2 km long road section with four signalized intersections and four bus services. Our results are summarized in Table 4. As expected, the a.m. scenario exhibits more lane changes than the p.m. scenario, caused by the relatively high traffic volume. With VROW, the average number of lane changes increased by about two for each vehicle group. This is caused by the vehicles to first make space for the approaching bus and then potentially changing back to the bus lane, based on equation (5), to make use of the free road segment ahead of the bus. This number is reduced to about 1.14 to 1.6 in the less congested p.m. scenario as the number of vehicles required to make space for an approaching bus is generally lower.

TABLE 4. **Average number of lane changes per vehicle.**

Vehicle types		Mixed	VROW	Δ
a.m.	Car	2.48	4.57	+2.09
	HGV	2.51	4.64	+2.13
	Motorbike	2.68	4.99	+2.31
p.m.	Car	2.20	3.52	+1.32
	HGV	2.43	3.57	+1.14
	Motorbike	2.30	3.87	+1.57

Our simulation results reveal that the VROW strategy offers tangible advantages to bus operation with tolerable impact on other traffic. The overall travel time for all traffic participants was reduced. Compared to a mixed lane strategy, the traffic safety risks induced by additional lane changes seem manageable. To summarize, when a full compliance rate of other vehicles can be achieved, VROW offers an alternative bus prioritization strategy that achieves a good balance for all transport modes compared to other existing strategies. Additionally, due to the dynamic and on-demand feature, VROW is suitable for locations where there is only a two-lane road, where bus volumes do not justify an exclusive bus lane, or where the impact of other priority strategies on private traffic would be too pronounced.

V. CONCLUSION AND FUTURE WORK

Dynamic bus lanes are a promising bus prioritization strategy because of their efficient usage of the road space. However, there still exist research gaps in the implementation and evaluation due to difficulties of realizing it in practice. We proposed VROW (Virtual Right of Way), a V2X-based dynamic bus lane concept. Through V2X communication, each vehicle in the network receives information of upstream buses as well as signal phases and timings, enabling them to execute collaborative lane changes when needed to make space for the approaching bus.

We implemented VROW in a microscopic traffic simulator and evaluated it in two scenarios, a synthetic highway and a real urban traffic scenario, calibrated to real traffic volumes and speeds. We compared VROW to existing bus prioritization strategies and observed that it offers a good balance between improved bus travel times and impact on other traffic. The dynamic clearing distance, which adapts to the traffic situations, offers better road space efficiency compared to static approaches. Depending on the traffic density, we observed that VROW caused between one and two additional lane changes in our signalized 1.2 km long simulation network. VROW can be applied on two-lane roads or where exclusive bus lanes are not feasible, assuming a 100% penetration rate of V2X technology.

In the near future, we are planning to conduct a field trial of the VROW system to better understand its feasibility in a real-world setting. Additionally, we would like to further investigate the impact of the activation period, the time/distance gap as well the compliance rate on the performance of VROW. Lastly, a more large-scale simulation study is needed to fully understand the potentials of VROW in an urban context, in particular when combining it with traffic signal prioritization methods.

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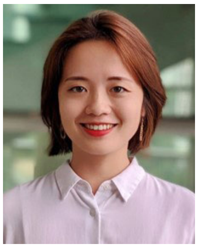

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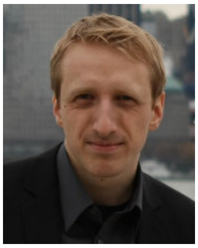

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