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Simulation of Reserved Lanes Along Signalised Arterials in Urban Areas for Autonomous Buses / Cavallero, A., Deflorio, F., Caroleo, B., Bellini, A.. - In: APPLIED SCIENCES. - ISSN 2076-3417. - ELETTRONICO. - 16:22(2026). [10.3390/app162211126]

Availability:
This version is available at: 11583/3017789 since: 2026-11-11T14:59:20Z

Publisher:
MDPI

Published
DOI:10.3390/app162211126

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17 November 2026

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Simulation of Reserved Lanes Along Signalised Arterials in Urban Areas for Autonomous Buses

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Abstract

The integration of autonomous buses into urban public transport offers opportunities to improve service efficiency in mixed traffic. Although lane reservation strategies have been extensively investigated for conventional public transport, their application to autonomous buses operating within urban transit services remains largely unexplored. This study analyses the applicability of different lane management strategies for an autonomous bus service operating along an existing route on a major urban arterial in Turin, extending current research beyond the low-speed shuttles in controlled environments typically considered in European studies. The study investigates different lane management options for autonomous public transport in a simulated road traffic environment and evaluates the effectiveness of the process of autonomous bus detection and lane activation logic, aiming to refine control strategies. For dynamic lane reservation, a local management approach is compared with respect to an arterial-based logic to evaluate the impact of dedicated lanes for autonomous buses, aimed at reducing interactions with general traffic, while limiting side effects to private vehicles. The preliminary results demonstrate, for the simulated Turin corridor, that full-corridor dynamic reservation with the arterial activation logic reduces autonomous bus travel and stop times, while producing smaller impacts on car speed compared to a basic permanent lane reservation.

Keywords: autonomous bus; traffic management strategies; dedicated lanes; traffic microsimulation; urban public transport; dynamic lane activation logic

Check for updates

Academic Editor: Seoungbum Kim

Received: 14 September 2026
Revised: 26 October 2026
Accepted: 2 November 2026
Published: 10 November 2026

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1. Introduction

In recent years, a growing amount of research and industrial effort has been devoted to the development, testing and deployment of autonomous vehicles (AVs). Their degree of automation is classified into six levels (0–5) by the Society of Automotive Engineers [1], according to the share of the Dynamic Driving Task (DDT) performed by the system within a specific Operational Design Domain (ODD). Driving automation is expected to contribute to the objectives of the Vision Zero initiative [2] by reducing crashes caused by human error, which remains one of the leading factors in road traffic fatalities and serious injuries. In addition, AVs may enhance accessibility for vulnerable users and contribute to more efficient and sustainable urban mobility.

Public transport is regarded as one of the most promising application fields for vehicle automation. Transit services operate on fixed routes with predefined stops, offering a well-

bounded ODD. Beyond the potential benefits of automation for vehicle control and safety, also explored through adaptive shared control strategies in human-driven vehicles [3], the deployment of fully automated vehicles could respond to operational challenges of the sector, such as driver shortages, service continuity and operating costs. To date, however, most of the European experimentation has relied on low-speed autonomous shuttles, i.e., small vehicles with limited capacity operating in protected or low-complexity environments, as in some pilot sites of the SHOW project [4], which included the Turin demonstration considered in this study. Although these trials have been valuable in assessing technological feasibility and user acceptance, the shuttle-based service model differs substantially from conventional public transport in terms of vehicle capacity, speed and route characteristics. A different perspective is emerging with the adoption of full-size autonomous buses, in line with initiatives such as the AutoDrive project [5] and the AutoMOST project [6], which enable service schemes directly comparable with those of traditional bus lines and thus outline a new paradigm for urban public transport.

The introduction of autonomous buses into urban networks nevertheless raises significant operational challenges, mainly related to their coexistence with human-driven vehicles. Differences in driving behaviour may affect traffic efficiency and interactions in mixed traffic (Xie et al. [7]).

During the transition phase, autonomous driving systems still tend to adopt conservative behaviours, including low operating speeds and cautious responses to surrounding traffic, which may increase delays and service variability. Rather than relying exclusively on vehicle technology, these interactions can be mitigated through infrastructure-side traffic management measures. Among them, lane reservation is a consolidated instrument to protect public transport: a lane may be statically reserved, i.e., permanently dedicated to transit vehicles, or dynamically reserved, i.e., activated only when a vehicle of the selected category is approaching and returned to general traffic otherwise, thus limiting the capacity penalty imposed on private vehicles.

In this context, Li et al. [8] proposed a dynamic bus lane strategy that exploits the capabilities of connected and autonomous vehicles to improve traffic efficiency, whilst maintaining priority for buses. Their study focuses on optimising vehicle access to bus lanes at signalised intersections, showing that the proposed strategy can reduce private car travel times by up to 22%, with improvements of up to 34% under higher traffic volumes.

Liu and Chang [9] developed an arterial signal optimisation model that explicitly captures the dynamic interactions between queues across lane groups and adjacent intersections, accounting for queue spillback and lane blockage under congested conditions.

From a different perspective, Sun et al. [10] developed a deep reinforcement learning approach to jointly optimise traffic signal phase sequences and timings, highlighting the potential of adaptive signal control to improve traffic operations. More recently, Wu et al. [11] proposed two models for coordinating traffic signals along urban arterials, considering not only traffic progression but also queue clearance and spillback prevention. The models increase green bandwidth along critical routes and, compared with existing approaches, reduce average vehicle delay and the number of stops, particularly under near-saturated traffic conditions.

Overall, these studies highlight the importance of an integrated, corridor-wide approach to arterial traffic management, accounting for queue dynamics and interactions between adjacent intersections.

Gu et al. [12], instead, developed a robust and adaptive simulation-based optimisation method, which allocates computational resources according to the variability of simulation results and the potential quality of candidate solutions. Their findings show that this

approach can identify optimal solutions more effectively than alternative methods under the same computational budget.

Although these studies do not directly investigate autonomous vehicles and dynamic bus lanes, they provide complementary insights into traffic management along corridors and the use of robust simulation-based optimisation methods for transportation problems.

This paper investigates lane management strategies to support a public transport service operated by 12 m autonomous buses along a signalised urban arterial. Unlike most European experiences, the analysis does not address a shuttle operating in a controlled environment, but autonomous buses running on an existing transit route in Turin (Italy), modelled in a microsimulation environment based on real infrastructure, traffic and service data. Static, dynamic and combined lane reservation configurations are compared against a no-reservation baseline and against the current fragmented layout of reserved lanes observed along the corridor. For the dynamic strategy, two detector-based activation logics are examined: a local approach, in which the reserved lane of each section is activated by the detection in the geometrically preceding section, and an arterial approach, in which the activation is anticipated at the nearest upstream signalised section. The objective is to identify a solution that is simple to implement and operationally efficient, able to reduce the travel and stop times of autonomous buses while limiting the side effects on private traffic.

The scientific literature on full-size autonomous buses has so far developed at two levels of abstraction. At the planning level, Tian et al. [13] formulated a multi-stage optimisation model for the progressive deployment of autonomous buses in a transit service network, in which the fleet conversion sequence is coupled with the evolution of passenger acceptance and shown to follow an optimal gradual, demand-responsive path. At the traffic flow level, Li et al. [14] developed an analytical model of mixed traffic composed of connected and autonomous buses, connected and autonomous vehicles, and human-driven vehicles, and used it to compare operations with and without dedicated bus lanes under different connectivity penetration rates. In both cases, the autonomous bus is treated as an element of a network- or link-level formulation: its microscopic operational behaviour, reduced operating speed, conservative interaction with surrounding vehicles, and the way this behaviour interacts with signal control and lane allocation along a specific corridor are not represented. Corridor-level analyses of autonomous bus operations under realistic infrastructure, signal timing and demand conditions therefore remain an open issue.

The European pilot experience [4,5] provides empirical evidence.

The SHOW demonstrations involved different types of autonomous vehicles, ranging from low-speed autonomous shuttles to full-size autonomous buses. The Turin pilot operated low-speed shuttles at approximately 20 km/h due to safety constraints, while other SHOW demonstration sites, such as Madrid, involved full-size autonomous buses. Other projects, such as AutoDrive, have instead focused on the technological developments required to enable the deployment of autonomous bus services.

Consequently, the behavioural parameters adopted in this study were calibrated using data collected during the Turin SHOW trial and subsequently confirmed by the results of other demonstration projects, including AutoDrive and AutoMOST, which showed comparable operating speeds for autonomous vehicles intended for public transport.

The lane management literature, by contrast, offers a mature methodological basis, although it is built on human-driven buses. For permanent reservation, the problem has mainly been addressed as a network design task: Bayrak and Guler [15] optimise the location of dedicated bus lanes while explicitly accounting for traffic dynamics, showing that the benefit of a reserved lane depends on congestion levels. Since a permanent reservation subtracts capacity from general traffic even when no bus is present, dynamic schemes have

been developed: the intermittent bus lane, demonstrated in the field in Lisbon by Viegas et al. [16], clears the lane only ahead of an approaching bus.

Subsequent studies coupled intermittent lanes with signal priority [17,18] and evaluated their capacity effects analytically.

Chiabaut and Barcet [19] provided further field evidence of intermittent operations, while Wang et al. [20] generalised the concept to dynamic road lane management in smart city applications.

The most recent contributions concentrate on three technical dimensions directly relevant to this study: the spatial–temporal granularity of the reservation [21,22], the control of variable bus lanes at signalised intersections [23] and the realism of the operating assumptions, including the effect of driver compliance rates on dynamic bus lane performance [24] and the simulation of dynamic bus lanes applied to real-world bus operations [25]. Two limitations recur across this stream: the analyses typically concern a single segment or an isolated intersection rather than a sequence of consecutive sections along an arterial, and the activation logic—where the detection trigger is located and, consequently, how much time private vehicles are granted to vacate the lane—is generally assumed a priori rather than treated as a design variable.

Three questions therefore remain open and define the scope of this paper: whether the benefits observed for traditional vehicles of dedicated lanes persist when the protected vehicle is a full-size autonomous bus operating a scheduled service on an existing route; how static, dynamic and hybrid reservation configurations perform when applied to consecutive sections of a signalised arterial, where the lane-clearing process in each section depends on the traffic reorganisation induced in the upstream ones; and how sensitive the performance of a dynamic lane is to the position of the activation detector, which determines the clearance time available before the autonomous bus arrives. These questions are addressed in the following sections.

2. Materials and Methods

2.1. Dynamic Lane Reservation (DLR) Concept

The dynamic reservation creates a priority lane for autonomous vehicles operating as public transport without requiring the construction of dedicated infrastructure or major changes to the existing network.

A dynamically dedicated lane strategy can provide the autonomous vehicles with a more controlled operating environment, reducing interference from private traffic and limiting the influence of heterogeneous driving behaviours. This allows the autonomous system to focus primarily on trajectory management and critical interactions, such as those with vulnerable users or unexpected obstacles (illegally parked cars), rather than frequent adjustments due to surrounding vehicles. In this mode, autonomous vehicles can follow their routes with less interference from surrounding traffic, benefiting from more uniform and predictable operating conditions. Consequently, the reduction in external constraints can improve operational stability, promote higher speeds, and increase service efficiency.

The dynamic lane reservation strategy is based on the detection of a specific category of vehicles, such as autonomous shuttles or buses, without reference to the identity of the individual vehicle or the transport route to which it belongs.

The dedicated lane is activated automatically when the detection systems identify a vehicle belonging to the selected category; when no such vehicle is present, the lane is made available to general traffic. The detection interval is determined by the simulation time step, with no additional latency assumed for strategy activation. The system is highly adaptable and scalable, allowing for the use of various types of autonomous vehicles and effectively responding to changing operational requirements.

2.2. DLR Activation Strategy with Local Approach

The strategy is implemented at the section level and is based on detecting the position of autonomous vehicles using sensors installed along their route. These sensors enable the dynamic lane to be automatically activated and deactivated depending on the presence of the autonomous vehicle. The operating logic of the dynamic lane is illustrated in Figure 1.

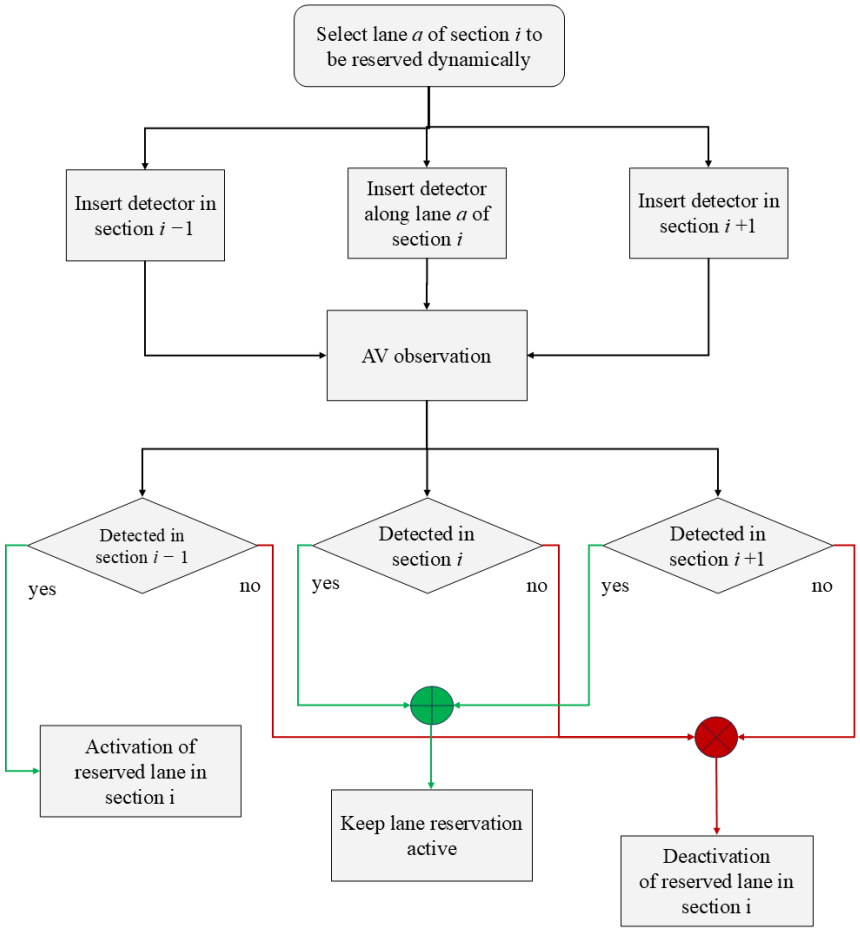


Figure 1. Chart of the Dynamic lane implementation methodology with local approach.

Considering the implementation of the strategy in section i, at least three detectors are required.

The first is positioned in section $i - 1$, upstream of the section affected by the dynamic lane; the second is located in the lane subject to dynamic reservation within section i; the third is installed in the subsequent section, $i + 1$.

The detector located in section $i - 1$ is responsible for the activation of the strategy. When the presence of an autonomous vehicle is detected, the dedicated lane in section i is reserved for its passage before its actual arrival. The sensor in section i confirms the vehicle presence within the relevant section, whilst the one installed in section $i + 1$ monitors its exit from the strategy area of influence.

The combined use of the three sensors ensures that the lane remains reserved for the entire duration of the autonomous vehicle passage, preventing any premature deactivation. The lane is only returned to general traffic once none of the three sensors detects the presence of autonomous vehicles. At that point, the previously reserved lane becomes available again to all road users.

For the dynamic reservation strategy to function correctly, the sensors must be positioned at specific locations to ensure adequate coverage of the autonomous vehicle route.

In particular, the sensor installed in section i − 1 plays a key role, as it enables the dynamic lane to be activated in advance.

For this reason, it must be positioned along section i − 1 to be of sufficient length to detect the autonomous vehicle before it enters section i.

This configuration ensures that the system has the necessary time to process the detection and activate the reserved lane before the autonomous vehicle arrives.

The detector positioned in the reserved lane a of section i must cover the entire length of the lane subject to dynamic reservation, ensuring continuous detection of the vehicle as it traverses the relevant section. This prevents any temporary loss of detection from causing the system to prematurely return the lane to general traffic, as seen in Table 1.

Table 1. Detectors for activation and deactivation for local approach.

Dyn Lane in Section	Activation	Deactivation		
	Detector $i-1$	Detector $i-1$	Detector i	Detector $i+1$
i	$i-1$	$i-1$	i	$i+1$

The configuration and sizing of the detectors were defined through an iterative calibration process in the micro-simulator, continuous priority management and reliable deactivation of the strategy.

To decrease the number of detectors required for the implementation of dynamic lane reservation along consecutive sections, a single detector was installed in the dynamically reserved lane of each section.

The detector covers the full length of the section to ensure continuous monitoring of the autonomous vehicle while it traverses the reserved area. This configuration prevents premature deactivation of the lane reservation strategy, which could otherwise occur if the detector length were shorter than the section length and the vehicle temporarily left the detection area before exiting the dynamically reserved section. The detector placed along each dynamically managed section is sufficient to perform three functions: activating the strategy in the next section (operating as detector i − 1), keeping the strategy active within the section itself (operating as detector i) and deactivating the strategy in the previous section (acting as detector $i + 1$).

2.3. DLR Activation Strategy with Arterial Approach

When the local section-based strategy is applied to consecutive urban sections, problems may arise due to insufficient time for conventional traffic to reorganise properly.

In particular, activation based on the immediately preceding section may not provide sufficient time for private vehicles occupying the lane to complete the necessary lane-changing manoeuvres and vacate the lane reserved for public transport, especially in case of non-signalised segments, where the flow of traffic is continuous.

By contrast, the arterial-based approach anticipates activation at the preceding signalised intersection, allowing vehicles more time to change lanes and clear the reserved lane before the autonomous bus arrives.

The activation detector, which in the local configuration is in section i − 1 (the section immediately upstream of section i), is replaced by a detector located in the i − 1 section with traffic lights (section $i - 1_{signalised}$).

Looking at Figure 2, under the previous strategy, the activation of the lane reservation in section i would have been triggered by a detector located along the roundabout. With this revised methodology, the activation detector is moved upstream and positioned in section $i - 1_{signalised}$, at the α signalised intersection.

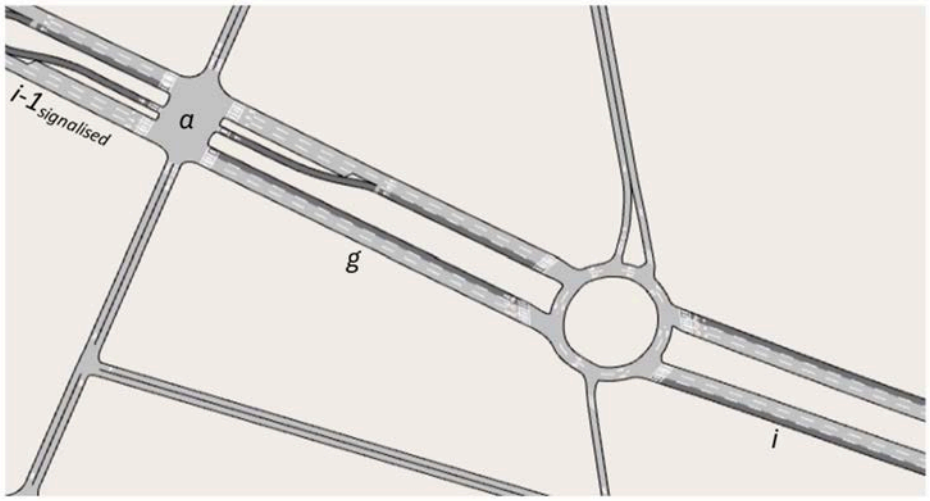


Figure 2. Activation logic in section i based on a detector located in section $i - 1_{signalised}$.

To prevent the strategy from being deactivated prematurely before the autonomous vehicle arrives in section i, it is necessary to ensure continuous monitoring of the vehicle by means of additional detectors installed along the intermediate sections, in section g and at the roundabout.

This modification allows the activation of the dynamic lane to be brought forward, increasing the time interval between the trigger and the autonomous vehicle entry into section i, as seen in Figure 3.

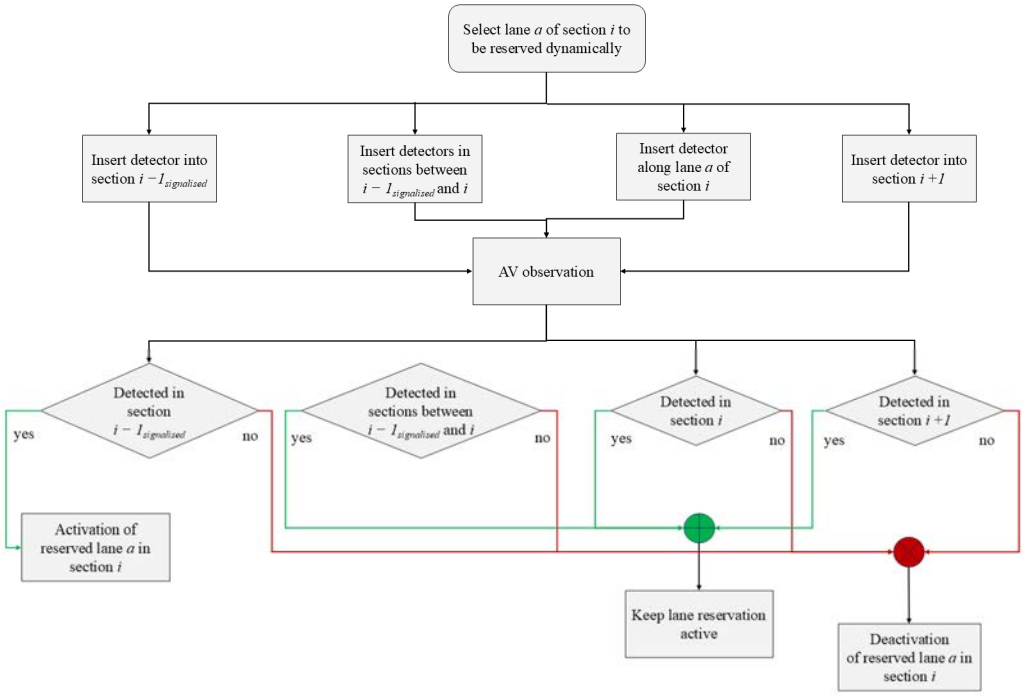


Figure 3. Dynamic lanemethodology with arterial approach.

In this way, road users have more time to reposition themselves and complete the lane changes necessary to clear the dedicated lane more gradually and safely.

The deactivation occurs only when the vehicle is no longer simultaneously detected by any of the sensors located between section $i - 1_{signalised}$ and section $i + 1$, ensuring that the

vehicle has fully exited the controlled area before releasing the dynamic lane, as illustrated in Table 2.

Table 2. Detectors for activation and deactivation for arterial approach.

Dyn Lane in Section	Activation	Deactivation			
	Detector $i-1_{signalised}$	Detector $i-1_{signalised}$	Detectors between $i-1_{signalised}$ and i	Detector i	Detector $i+1$
i	$i-1_{signalised}$	$i-1_{signalised}$	g, *roundabout*	i	$i+1$

2.4. Testing Approach

A microscopic traffic simulation approach was adopted to assess the performance of the different lane reservation strategies.

After selecting the study area, the model was implemented in the micro-simulator using OpenStreetMap (OSM) data and subjected to a calibration process aimed at reproducing reality as faithfully as possible. During this phase, any geometric inaccuracies were corrected, with reference to the number of lanes, the representation of nodes, pedestrian crossings and local narrowing.

The calibration process of the traffic model also involved defining the turning movements and traffic signal control to ensure consistency with the real-world infrastructure. Furthermore, some turning movements were reconfigured in the microsimulation model by introducing additional right-turn manoeuvres from the adjacent lane, ensuring that private vehicles could maintain right-turn accessibility when the rightmost lane was reserved for public transport.

Private traffic demand was represented through an origin–destination (OD) matrix, while public transport services were modelled using predefined scheduled routes, based on real-world observations, ensuring that the simulated service could be representative of realistic operating conditions.

To obtain interesting cases for evaluating the management strategies, demand was defined following an iterative process to generate critical traffic interactions consistent with observations. Indeed, an iterative procedure has been applied for the origin–destination matrix estimation to generate queues and delays at specific approaches of the intersections along the main corridor, to be consistent with speed observations in peak hours derived from the TomTom Move dataset for the road sections of the study area.

Once the calibrated model was established, the different lane reservation scenarios and activation approaches were implemented, and multiple simulation runs were performed to compare the performance of each strategy under the same traffic demand conditions.

To implement the lane reservation scenarios, a specific lane management configuration for public transport was assigned to each section of the corridor.

Specifically, three possible operating conditions were considered for each section: no reserved lane, a permanent reserved lane, or a dynamic reserved lane.

This approach allowed the analysis of how different combinations of static, dynamic, and non-reserved sections influence the overall performance of the transport system, while also evaluating strategies aimed at ensuring a continuous priority corridor for public transport, including services operated by autonomous buses.

In the case of autonomous buses, the presence of dedicated lanes plays a significant strategic role.

In addition to leading to increases in commercial speed and service regularity, separation from private traffic allows for a significant reduction in vehicle interactions, reducing exposure to unexpected manoeuvres that could be critical for autonomous driving systems.

Starting from these three elementary configurations, five different simulation scenarios were constructed, obtained by assigning different lane management strategies to the individual sections.

The "RES Never" scenario represents the case in which the right lane is not reserved for public transport in any section of the corridor. In this configuration, the autonomous bus operates in mixed traffic conditions, sharing the carriageway with private vehicles. This scenario serves as a baseline, useful as a reference for evaluating the performance of alternative strategies, as it allows for no separation between private traffic flows and public transport. Consequently, it represents the lower limit in terms of priority given to public transport.

The "RES Real" scenario represents a common real-world scenario in which public transport fixed reserved lanes are provided only in selected sections of a corridor, while no lane reservation is applied in the other sections, resulting in a fragmented implementation rather than a continuous reserved facility. This scenario was therefore defined as a benchmark against the real-world configuration to assess the effectiveness of the alternative strategies proposed in the other scenarios.

The "RES Always" scenario considers an extreme configuration in which all the sections of the corridor are permanently reserved for public transport. This configuration represents an upper limit on the priority granted to public transport: on the one hand, it may restrict the flow of private vehicles; on the other, it constitutes an ideal situation for the public transport operator, which benefits from an exclusive lane.

Finally, two dynamic scenarios have been defined, activating and deactivating dynamically depending on the passage of the autonomous buses.

The "RES DynPart" scenario adopts a hybrid lane management configuration based on the real-world network. Static reserved lanes in selected sections are maintained, while the remaining sections are subject to dynamic activation and deactivation of the reserved lanes.

This approach combines the preservation of the existing infrastructure with a dynamic management strategy in the remaining sections of the corridor, where no lane management is applied, to ensure greater continuity of public transport priority while remaining consistent with observed real-world conditions.

Finally, the "RES DynFull" scenario involves applying the dynamic reservation strategy to all the sections of the corridor, ensuring fully flexible management of the reserved lane along the entire axis analysed and reducing the permanent occupation of road space.

For the two dynamic lane reservation configurations, the two activation approaches were evaluated: the local and the arterial-based.

Since autonomous buses are assumed to be fully integrated into the existing public transport fleet, the dedicated lanes were not reserved exclusively for autonomous vehicles but were designed to be accessible to all public transport services, regardless of vehicle type. This approach reflects the objective of supporting public transport as a whole, extending priority benefits to both automated and conventional services operating within the urban transit system.

After setting up the network and defining the lane management scenarios, the simulations were run after a 10 min warm-up period to start with stationary traffic conditions before collecting and analysing the outputs.

3. Case Study

To evaluate and compare the lane management strategies and the management of the dynamic reservation, a case study focusing on the city of Turin was considered.

The analysis was conducted using the Aimsun Next micro-simulator [26], which enabled the implementation and testing of the different strategy configurations on an urban corridor.

The study aimed to evaluate the introduction of autonomous vehicles, specifically 12 m autonomous buses, operating on an existing public transport route, with a view to improving operational efficiency.

In particular, the effectiveness of dynamic lane management along several consecutive sections of the corridor was analysed to ensure that the rightmost lane is reserved for autonomous and traditional public transport.

Three additional lane management configurations were analysed alongside the dynamic strategy: a baseline scenario with no reserved lanes and full mixed traffic operation, a scenario with permanently reserved right lanes for public transport, and a real configuration combining reserved and non-reserved sections along the corridor, as observed in reality.

3.1. Study Area and Network Construction

3.1.1. Study Area

To build the simulation model in Aimsun Next, the first step was to select the study area, identified as the southern part of the city of Turin, in line with the trials conducted as part of the Turin pilot of the SHOW project [4]. The analysis was subsequently extended to the entire Corso Maroncelli corridor, which was selected as a representative case study due to its three-lane configuration, its diverse infrastructural features and its high volume of traffic. The study area was imported into the simulator, and inconsistencies in the road network geometry were corrected to ensure an accurate representation of the real infrastructure.

3.1.2. Road Traffic Modelling

Traffic light controls and turning manoeuvres were defined on the basis of observations of actual operating conditions. On sections where the rightmost lane could be reserved for public transport, right turns from the adjacent lane were also permitted, to ensure that private vehicles could still make such manoeuvres when the right lane was not available to them. Once the network infrastructure and traffic light controls at major intersections had been defined, traffic demand was introduced by specifying the vehicle types. A maximum speed of 50 km/h was imposed, in line with the urban speed limit.

Demand for private cars was generated using an origin–destination matrix, employing an iterative procedure designed to generate critical traffic interactions and queues at identified intersections along the main corridor, to be consistent with the traffic conditions observed for speed values in peak hours of road sections in the TomTom Move dataset. Instead, public transport services were modelled using pre-defined routes based on existing real-world operations.

Traffic Signals

The allowed manoeuvres and the traffic-light-controlled intersections (A, B, C, D, E, F and G in Figure 4) along Corso Maroncelli were modelled and calibrated, including their traffic light cycles.

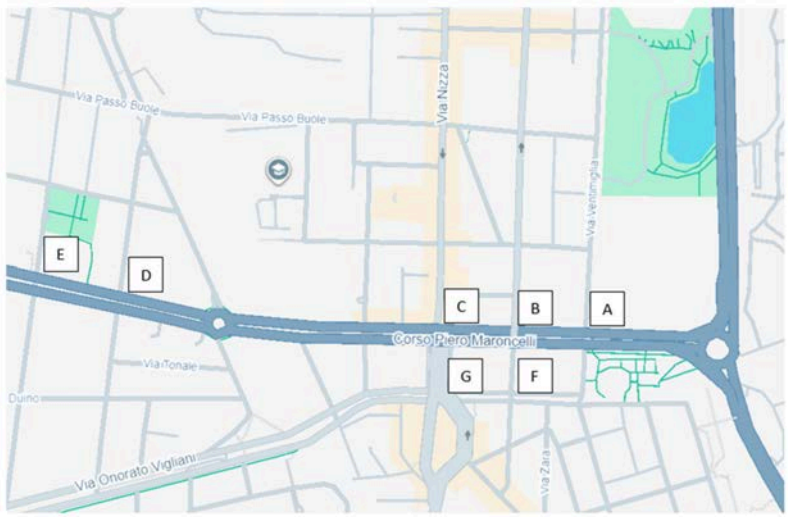


Figure 4. Study area and seven signalised intersections (from A to F), from Google Earth accessed 15 June 2026.

Traffic Flow Setting

In the simulation model, vehicle categories and traffic flows were incorporated. Specifically, three vehicle types were modelled: traditional private cars, conventional buses operating on public transport, and autonomous 12 m buses.

Concerning the geometric and performance characteristics of the vehicles, the default parameters included in the micro-simulator were used for private cars and traditional buses.

For autonomous buses (A Bus), a specific vehicle was introduced, modelled with reference to the characteristics of the Irizar i2e bus model [27], to represent its operational behaviour more realistically, as seen in Table 3.

Table 3. Vehicles characteristics.

Type of Vehicle	Max Speed [km/h]	Length [m]	Width [m]	Acceleration [m/s^2]	Deceleration [m/s^2]	Reaction Time [s]
Private cars	50	4.00	1.80	3	4	0.8
Bus	50	12	2.50	1	2	0.8
A Bus	20	12	2.50	0.9	1.6	0.4

The conservative behaviour of autonomous buses is represented through lower operating speeds and shorter reaction times, while retaining the same car-following model used for conventional vehicles. This parameter was adjusted to reflect that autonomous vehicles exhibit more consistent behaviour and shorter reaction times (representing the overall perception–planning–actuation latency) than conventional vehicles.

To keep the simulation process consistent, the reaction time parameter must be a multiple of the simulation step, set at 0.2 s. The simulation step represents the time interval at which the model is updated within the micro-simulator and directly influences the temporal resolution of the simulated traffic dynamics.

The choice of 0.2 s represents a compromise between the accuracy of the system representation and computational cost, avoiding an excessive computational load whilst maintaining good precision in the simulation of vehicle interactions. For this, the reaction time of autonomous buses was set at 0.4 s, a value chosen to be consistent with the literature [28] and at the same time lower than that assigned to general vehicles, ensuring a clear behavioural distinction between the two categories.

The speed limit and the stop time for autonomous buses have been obtained not only from bus operators but also from most projects in which autonomous buses have been implemented and tested in urban real cases (e.g., SHOW [4], AutoDrive [5]).

Although these buses can also travel at higher speeds, for real-life applications, the approach adopted by stakeholders in charge of responsibility in case of an accident is prudent and, for safety reasons, a lower speed is usually set for the service. This approach, on the one hand, mitigates the risk of collisions and their severity, but on the other hand requires some traffic management strategies to support the service in reducing interactions with other vehicles.

However, a speed factor of 1.0 with a standard deviation of 0.1 was assigned in the microsimulation model to account for variability in operating speeds.

Although conservative, it is considered appropriate for the present study, with the expectation that future technological and regulations developments may allow higher operational speeds.

Private Traffic Demand

For private traffic, the flows were defined using an OD matrix (Table 4) to represent interactions through a synthetic demand specifically designed to generate representative traffic flows along the study corridor.

Table 4. ODmatrix for private cars.

	1	2	3	4	5	6	TOT
1	0	300	150	250	200	200	**1100**
2	300	0	0	0	250	200	**750**
3	150	0	0	150	0	0	**300**
4	250	0	150	0	200	200	**800**
5	200	250	0	200	0	0	**650**
6	200	200	0	200	0	0	**600**
TOT	1100	750	300	800	650	600	**4200**

The OD structure was constructed using six centroids to balance detail and simplicity in the model.

The first three centroids represent the main access points to the Corso Maroncelli corridor: direct entry and exit flows and flows channelled through the roundabout. Centroid 4 represents flows coming from and heading towards the neighbouring area of Nichelino, characterised by multiple connections.

These connections have all been retained in the model, but differentiated by means of a percentage allocation, with higher shares assigned to the main access sections and lower shares to the secondary access points. Finally, centroids 5 and 6 represent the flows coming from the eastern and western areas of Turin, respectively, contributing to a more complete description of the system boundary conditions, as seen in Figure 5.

Indeed, an iterative procedure has been applied for the demand definition to generate queues and delays at the approaches of the intersections along the main corridor. The speed reduction before the main intersections has been used as a proxy for the queue length. The delays observed in the baseline scenario in Figure 6, in which no lane-management or control strategies are applied, are consistent with the traffic conditions along the main corridor derived from the TomTom Move dataset for the study area, as reflected by the harmonic average speed shown in Figure 7.

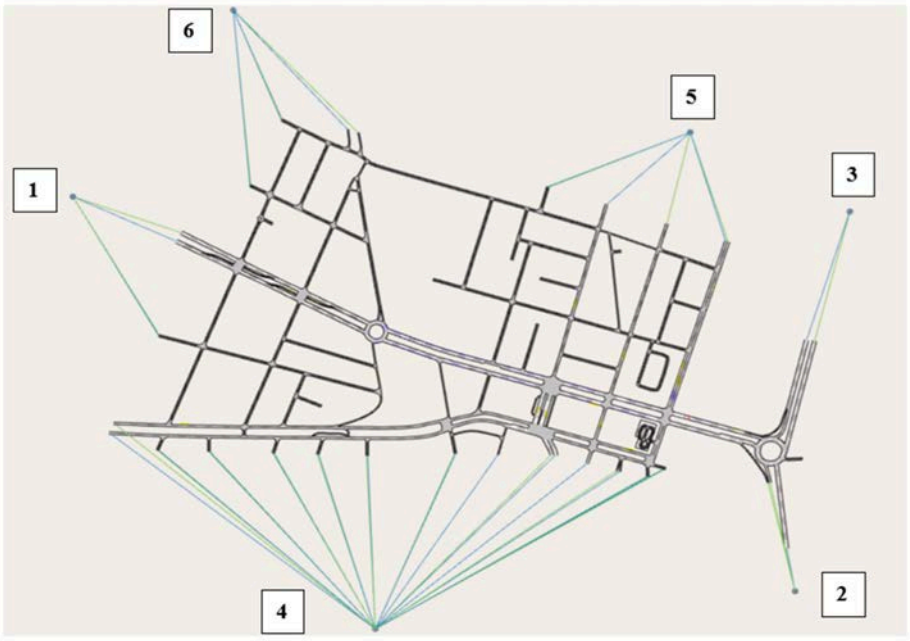


Figure 5. 6 selected entroids connected to the road network in the study area.



Figure 6. Delay time (highlighted with colours in the scale from green to red) observed for the road sections of the study area in traffic microsimulation.

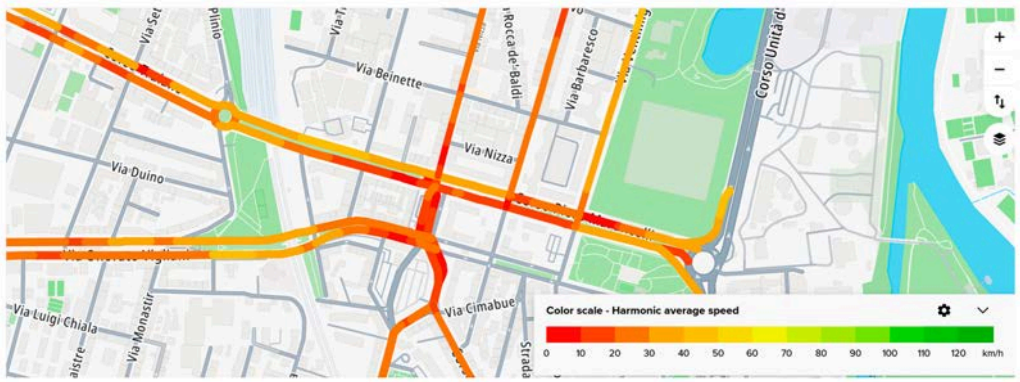


Figure 7. Speed values (harmonic average) observed by TomTom Move data and represented by the color scale

Public Traffic Demand

As regards public transport, the implementation was carried out by defining the fixed routes, available on the GTT-Gruppo Torinese Trasporti website [29].

All routes passing through the Corso Maroncelli corridor were modelled, including paths, stops and stopping times. The implementation methodology was consistent between traditional and autonomous transport, but with different operational parameters. Traditional 12 m buses have a stop time of 15 s and an average frequency of approximately one vehicle every 10 min, with a ±2 min variation introduced to reflect operational variability in urban services, as observed in the field.

For routes with a terminus within the study area, continuous route modelling was adopted: upon reaching the terminus, the vehicle stops for 8 min and departs in the opposite direction, avoiding the need to re-enter the network and ensuring the continuity of the simulated service. For routes without an internal terminus, the two directions of travel were modelled separately.

The same logic was also applied to the route served by autonomous buses, which was the subject of the study. The selected bus line was chosen among the existing routes because it operates along the entire study corridor in both travel directions.

In this case, however, the stopping time at bus stops was increased to 25 s to allow for stopping manoeuvres, whilst the frequency was kept fixed (one vehicle every 10 min) with no variation, to represent a more regular and controlled service compared to traditional public transport.

3.2. Service Management Settings and Simulation Experiments

3.2.1. Lane Reservation Scenarios Definition

In the real configuration, the infrastructure analysed is characterised by the presence of lanes reserved for public transport; however, these lanes are currently discontinuous and limited to specific sections of the network.

To overcome this fragmentation, simulation scenarios have been defined that introduce a more continuous management of the reserved lane along the corridor to increase the priority of public transport and assess its effects on both the operational performance of the service and general traffic conditions.

For the comparative analysis of the various lane management strategies on consecutive sections, a corridor approximately 700 m long along Corso Maroncelli was selected, comprising the section between roundabout R and intersection A.

As shown in Figure 8, ten sections of the corridor have been identified—five in the outbound direction and five in the inbound direction—in which the right lane is subject to a lane management strategy.

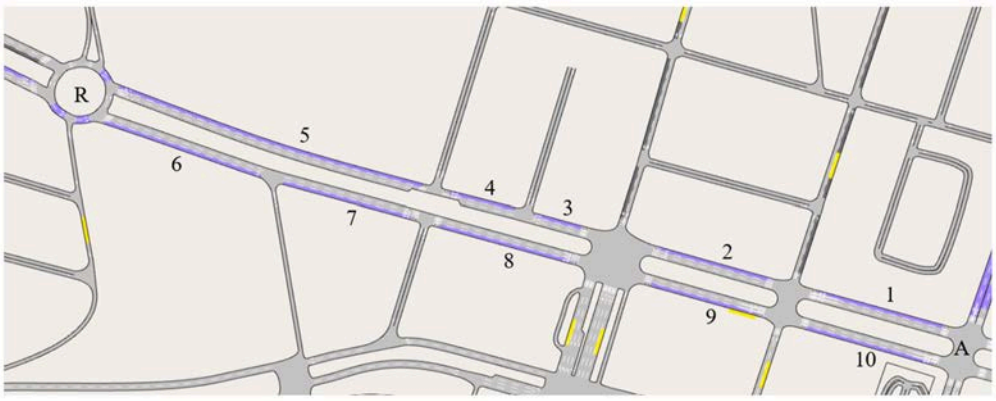


Figure 8. 10 sections identified for lane management strategies with detectors highlighted in violet.

Table 5 presents the five analysed scenarios, during the one hour of simulation, by specifying the lane management strategy applied to each of the ten corridor sections, according to the three available configuration types (no, fixed or dynamic reservation).

Table 5. Lane management strategy adopted in each section of the corridors for the five scenarios.

	Lane Management Strategy		
Scenario	**Never Reserved**	**Always Reserved**	**Dynamic Reserved**
RES Never	1–10	-	-
RES Real	1–4, 7, 8, 10	5, 6, 9	-
RES Always	-	1–10	-
RES Dyn Part	-	5, 6, 9	1–4, 7, 8, 10
RES Dyn Full	-	-	1–10

3.2.2. Use Cases to Compare Lane Reservation Strategies for Two Dynamic Managements

The objective of the experiments is twofold: (i) to compare different lane reservation strategies along the corridor; and (ii) within the context of dynamic management, to identify the most effective activation methodology.

To this end, two use cases were developed.

The local management case comprises the five scenarios, with the dynamic strategy implemented according to the local approach.

The arterial management case considers the same scenarios but applies the arterial methodology to dynamic management to evaluate its performance compared with the local approach.

In both cases, dynamic lane reservation is activated upon the detection of the autonomous bus. Once activated, the reserved lane is available to both autonomous and conventional buses, with the aim of improving public transport operations overall.

Local Management

In the first use case, the dynamic strategy is implemented according to the local methodology, based on the activation through the detector $i - 1$ in the geometrically preceding section.

Consequently, a detector has been positioned in the right lane of each section, dedicated to managing the activation and deactivation of the dynamic lane along the corridor.

Figure 9 shows the layout of the detectors implemented in the microsimulation, highlighted in purple in each section where the dynamic lane is active (d1–d10).

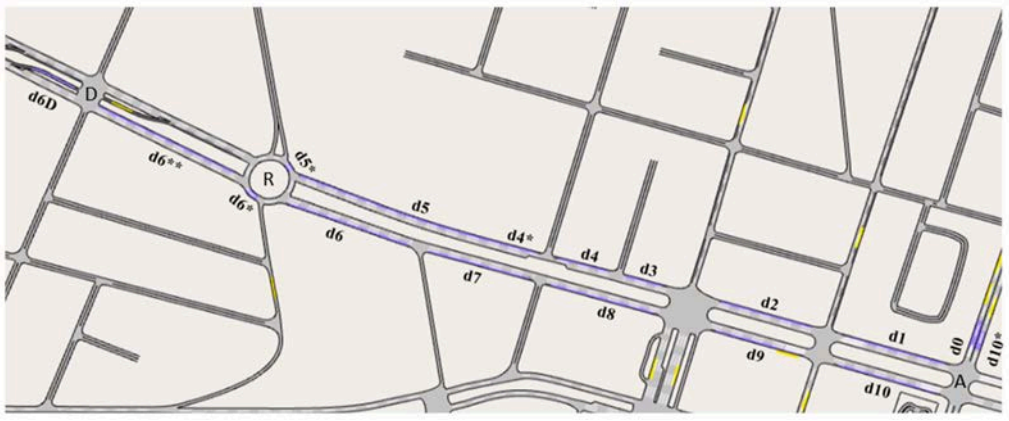


Figure 9. Position of the detectors highlighted in violet and identified with their code in the new detection strategy based on section $i-1_{signalised}$, image from Aimsun Next micro-simulator model[Aimsun, Barcelona, Spain].

Additional detectors control the activation and deactivation of the strategy at the boundaries of the corridor: d0 and d6* activate the strategy at the start of the outbound and return sections, whilst d5* and d10* deactivate it in the final road sections (5 and 10). A further detector (d4*), positioned at the start of road section 5, is used to deactivate the strategy in road section 4.

This additional detector was introduced due to the considerable length of road section 5. Without it, the deactivation of road 4 would depend on the detector in 5, causing an excessive delay in switching off the strategy, as vehicles would remain within the detection area for an extended period.

The intermediate detector therefore allows for a more immediate and accurate deactivation process.

Table 6 summarises the configuration by reporting, in the first column, the ID of each section where the dynamic lane is activated on the rightmost lane, along with the three detectors used to activate and deactivate the strategy within each section.

Table 6. Detectors necessary to implement the dynamic lane strategy in each of the ten sections for local reservation.

	Activation	**Deactivation**		
Dyn Lane in Section	**Detector $i-1$**	**Detector $i-1$**	**Detector i**	**Detector $i+1$**
1	d0	d0	d1	d2
2	d1	d1	d2	d3
3	d2	d2	d3	d4
4	d3	d3	d4	d4*
5	d4	d4	d5	d5*
6	d6*	d6*	d6	d7
7	d6	d6	d7	d8
8	d7	d7	d8	d9
9	d8	d8	d9	d10
10	d9	d9	d10	d10*

Arterial Management

In the second methodology proposed for consecutive sections, the dynamic activation of lanes is activated at the nearest preceding section equipped with traffic lights (section $i - 1_{signalised}$). Compared with the previous configuration, additional detectors have been installed to manage this logic.

Specifically, the d6D detector has been installed to activate the strategy on sections 6, 7 and 8, whilst a second detector, d6**, has been introduced to maintain activation along the section between node D and the roundabout R, as seen in Figure 9. This approach prevents the strategy from being deactivated prematurely in cases where the autonomous bus is not detected in the downstream sections, ensuring that the lane reservation remains constantly active in sections 6 to 8.

The strategy remains active as long as the autonomous bus is detected by all detectors between section $i - 1_{signalised}$ and section $i + 1$.

Table 7 lists the detectors used to activate and deactivate the dynamic lane in each of the ten sections of the Corso Maroncelli corridor.

In the "RES DynPart" scenario, dynamic activation is applied to all sections except sections 5, 6, and 9, where the static configuration is maintained. In contrast, the "RES DynFull" scenario involves dynamic activation across all ten sections of the corridor.

In both cases, the rightmost lane is dynamically activated and deactivated using one of the two proposed methodologies, depending on the specific use case configuration.

Table 7. Detectors necessary to implement the dynamic lane in each of the ten sections with an arterial detection strategy.

	Activation	**Deactivation**			
Dyn Lane in Section	**Detector $i - 1_{signalised}$**	**Detector $i - 1_{signalised}$**	**Detectors between $i - 1_{signalised}$ and i**	**Detector i**	**Detector $i + 1$**
1	d0	d0	-	d1	d2
2	d1	d1	-	d2	d3
3	d2	d2	-	d3	d4
4	d2	d2	d3	d4	d4*
5	d2	d2	d3 d4	d5	d5*
6	d6D	d6D	d6** d6*	d6	d7
7	d6D	d6D	d6** d6* d6	d7	d8
8	d6D	d6D	d6** d6* d6 d7	d8	d9
9	d8	d8	-	d9	d10
10	d9	d9	-	d10	d10*

3.3. Outputs of the Simulation

For the two cases, indicators were calculated as the average of ten simulation replications, increasing the robustness of the estimated performance, to assess the effects of the lane management strategies and the achievement of the defined objectives, as seen in Table 8.

Table 8. Results configuration selected (with X) for eachindicator

Results	Indicator	Unit	Time Aggregation		Space Observation			Vehicle Type	
			1 h	10 min	Section	Subpath from A to R	Subpath from R to A	Car	A Bus
Objectives evaluation	Travel time	min	X	-	-	X	X	-	X
	Stop time	sec	X	-	-	-	X	-	X
	Speed	Km/h	-	X	X	-	X	-	X
Side results	Lane changes	#/veh	-	X	X	-	-	X	-
	Speed	Km/h	-	X	-	X	X	X	-

Indeed, the lane reservation configurations and the different activation mechanisms for the dynamic lane were primarily aimed at improving the performance of the public transport service operated by autonomous buses. For this reason, the indicators of stop time (time spent at a stop per vehicle), travel time (average time it takes a vehicle to traverse the corridor) and speed were assessed for the autonomous buses in the most critical section and along the subpaths defined in both directions of travel: from intersection A to roundabout R, as seen in Figure 10, and in the opposite direction, from R to A, as seen in Figure 11.

Section 8 was considered and identified as the most critical point on the network. At this section, in fact, traffic flows from upstream sections converge without encountering any signal-controlled intersection and are subsequently regulated by the traffic lights at the end of the section itself.

This configuration can generate congestion and create traffic reorganisation problems, as vehicles are unable to redistribute themselves effectively and vacate the bus lane, making it particularly significant for the analysis.

Travel and stop time are shown as average values for the entire simulation period. Speed, instead, is presented as average values grouped into 10 min intervals to present its variation over time during the simulation hour.

Finally, the side results were analysed: the secondary effects of the strategies on other network users.

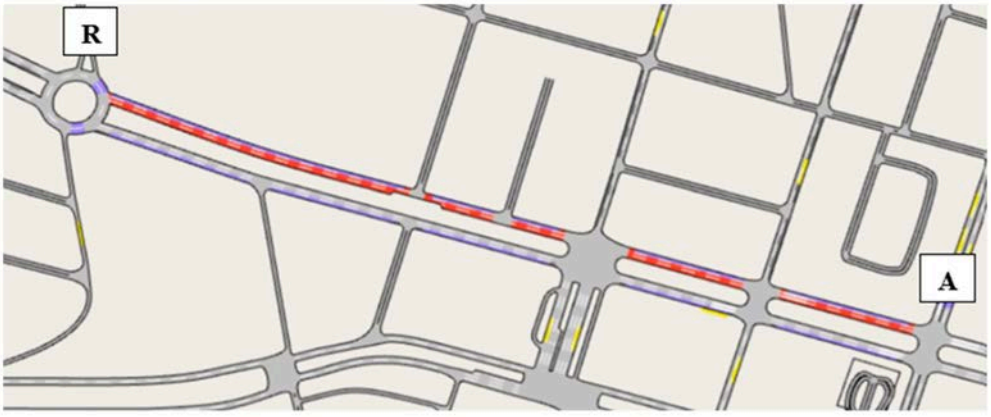


Figure 10. Subpath from intersection A to roundabout R in red and detectors in violet, from Aimsun Next micro-simulator.



Figure 11. Subpath highlighted in red from roundabout R to intersection A and detectors in violet, from Aimsun Next micro-simulator.

Once the effectiveness of the various configurations in improving the performance of autonomous buses had been verified, it was deemed important to assess any negative impacts on private traffic.

To this end, the lane-changing indicator per vehicle was analysed in the critical section to evaluate whether the lane management strategies could generate potentially critical situations because of the activation and deactivation of the reserved lane.

The potential reduction in road capacity is one of the side effects that can be observed in the simulation when applying the different strategies. Road capacity is indirectly assessed through the reduction in the average speed for other traffic.

For this, also, the speed indicator relating to private vehicles was assessed, extended to subpaths in both directions of travel, to verify whether the different strategies produced different overall effects along the outward and return journeys.

4. Results and Discussion

This section presents the results obtained for the two management approaches analysed.

For each case, the different lane reservation strategies are compared to identify the most effective scenario in terms of the A Bus performance. Subsequently, the comparison between the two cases allows for assessing which dynamic lane implementation methodology is more effective, comparing the local approach with the arterial management.

The results are organised into two main categories: objective results and side results. The former concern indicators that are directly related to the research objectives and are aimed at assessing the extent to which the proposed strategies promote autonomous bus transit and improve service performance. The side effect results analyse the indirect effects of the reservation strategies, which may impact private vehicles.

For each indicator analysed, the results for the local management are first presented, followed by those for arterial management.

4.1. Objectives Evaluation

By analysing the travel time for the autonomous buses, calculated as the average value over the entire simulation duration, it is possible to observe how this indicator varies with the scenario considered. With reference to the dynamic lane strategy implemented according to the local management methodology, in the direction from intersection A to roundabout R, the travel time remains virtually constant regardless of the scenario analysed.

This result highlights how the adoption of lane reservation strategies, whether static, dynamic, or hybrid, does not significantly vary the autonomous buses' travel time in this direction, ensuring essentially equivalent performance.

However, considering the implementation of the dynamic lane according to the arterial management methodology, the situation remains essentially unchanged.

The autonomous buses' travel time remains nearly constant for all scenarios analysed, highlighting how adopting a different dynamic lane activation methodology does not result in appreciable additional benefits in terms of travel time.

This behaviour can be explained by the fact that, in this direction, generally the geometrically preceding section used for the dynamic lane activation according to the local management methodology coincides with the preceding signalised section used in the arterial management approach. Consequently, the two methodologies activate the dedicated lane under very similar conditions, resulting in substantially similar performance for the autonomous buses.

Considering the direction between roundabout R and intersection A, as seen in Figure 12, the average travel time of A Bus along the subpath shows significantly different variations between the five scenarios analysed.

The most favourable scenario with the local approach is the one in which all sections are permanently reserved ("RES Always"), as it guarantees the shortest travel times. Conversely, scenarios characterised by dynamic lane reservation show significantly higher travel times, exceeding those recorded in the "RES Never" scenario, in which no lanes are reserved. Specifically, the "RES DynFull" configuration increases travel time by 14.24% compared to the latter scenario.

This result highlights that dynamic lane activation based on a local approach may not provide the same benefits as permanent reservation, as private vehicles have limited time to reorganise the lane usage before the autonomous bus arrives. This limitation is related to the timing of activation: under the local approach, activation is triggered by the immediately preceding section, which sometimes does not include a signalised intersection. Consequently, vehicles queued at the downstream traffic signal may not have sufficient time to clear the lane. By contrast, the arterial-based approach anticipates activation at the preceding signalised intersection, allowing queued vehicles more time to select the right lane.

As a result, the arterial-based management methodology achieved shorter travel times than the local management approach, with a reduction of 1.82 min (30.61%) when comparing the two "RES DynFull" scenarios. The solution that guarantees the shortest travel times is one in which all sections of the corridor in this direction are dynamically reserved. In fact, comparing within the arterial management the "RES DynFull" scenario with the "RES Never" one, in which no lane is reserved, travel time is reduced to 1.08 min (20.73%).

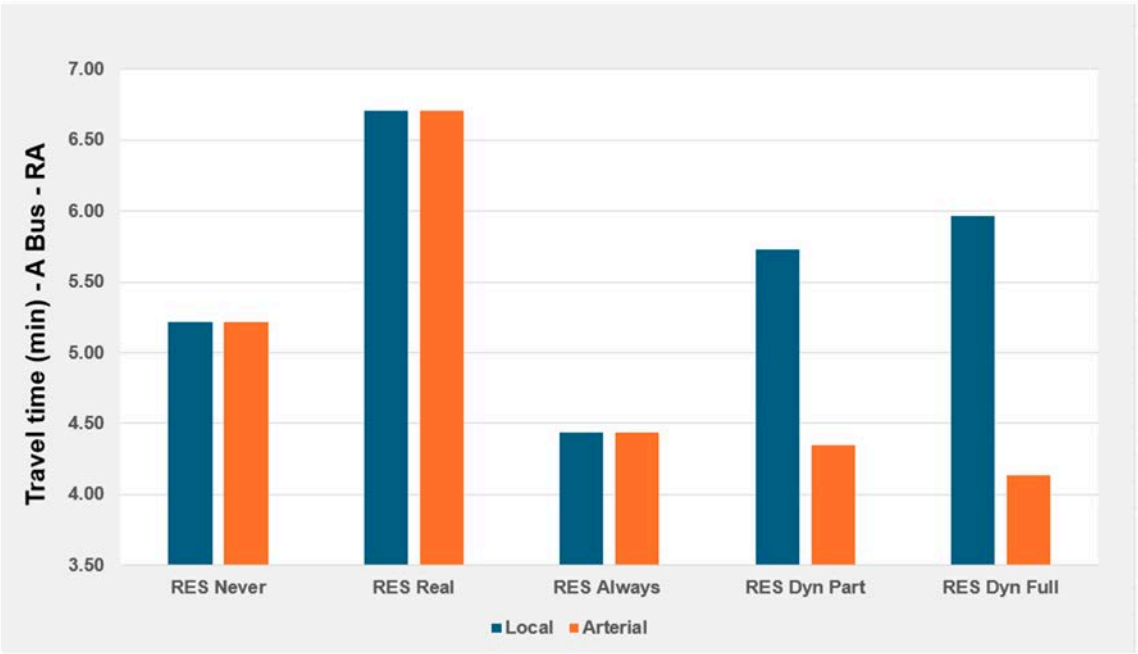


Figure 12. Travel time of the autonomous bus during the simulation for each lane management scenario in the direction from roundabout R to intersection A, referred to as the local and arterial management approach.

This result highlights how early activation of the dynamic lane can yield benefits greater than those achieved with a permanently reserved lane, while maintaining higher flexibility in the use of road infrastructure.

Interestingly, the "RES Real" scenario, which reflects a real-world configuration characterised by permanent reserved lanes but in fragmented form along the corridor, is among the most disadvantageous solutions in terms of performance.

The discontinuity of reserved lanes, in fact, leads to lower overall efficiency compared to a continuous configuration along the entire corridor. In particular, the fragmentation of dedicated sections creates critical issues with the operational regularity of the service, reducing the expected benefits for the autonomous buses.

Consequently, the continuity of the reserved lane along the corridor represents a key factor in ensuring better performance compared to fragmented configurations.

Considering the RA direction (from roundabout R to intersection A), which appears to be the most critical and the one where the greatest differences between the different dynamic lane management strategies are observed, the stop time graphs were analysed for both activation methodologies, local and arterial management (Figure 13).

The findings obtained are consistent with those observed for travel time. In particular, the local management approach resulted in substantially higher stop times for both the partial and full dynamic reservation scenarios, indicating that the introduction of a dynamic lane does not provide benefits in terms of reducing stops for the autonomous bus. On the contrary, it increases the overall stop time, reflecting the challenges associated with traffic reorganisation and the timely evacuation of private vehicles from the reserved lane. Comparing the "RES DynFull" scenario with the "RES Never" one, a significant increase in stop time of approximately 45.54% is observed.

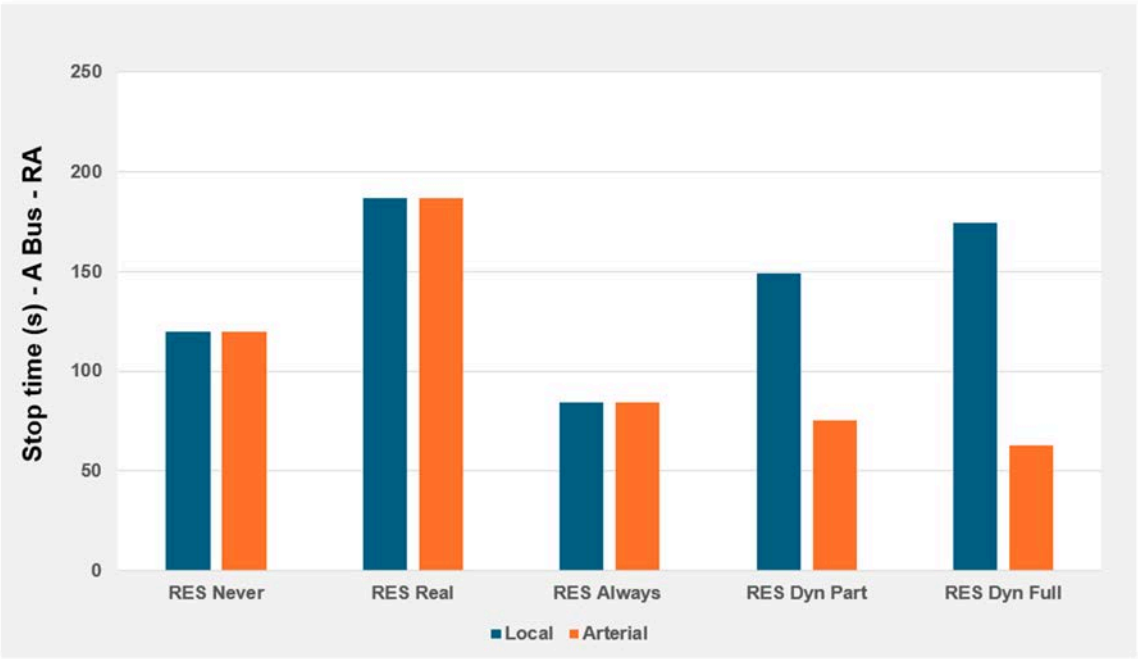


Figure 13. Stop time of the autonomous bus during the simulation for each lane management scenario in the direction from roundabout R to intersection A, referred to as the local and arterial management approach.

Conversely, the application of the arterial management methodology leads to a significant reduction in stop time for the dynamic scenarios. Specifically, the "RES DynFull" scenario shows the lowest values, with a reduction equal to approximately 47.52% compared to the baseline scenario "RES Never."

This result confirms how extensive management along the arterial road allows for better coordination of vehicle flows, reducing interruptions for the autonomous buses and improving their operational regularity.

A comparison of the speed graphs shown in Figures 14 and 15 also highlights significant differences between the two dynamic lane management methodologies. The speed graphs show the average speed of the autonomous buses for the RA direction, during the entire simulation period, between 10:00 and 11:00. The values are represented with a temporal discretisation of 10 min.

In the case of local management, the "RES Always" scenario represents the most effective solution in terms of speed.

Conversely, by adopting a methodology based on arterial management, dynamic reservation scenarios achieve even higher performance than the "RES Always" scenario. Compared to the baseline "RES Never" scenario, the "RES Always" scenario increases average speed by 16.17%, while dynamic implementation "RES DynFull" achieves an increase of up to 25.88%.

This result confirms how early activation of the dynamic lane along the entire arterial road increases the speeds for the autonomous buses, achieving performance superior to that achievable with a permanently reserved lane.

Analysis of the average speed graphs confirms what was observed for the other indicators.

The scenarios that guarantee the best performance in terms of speed are those characterised by the presence of continuous reserved lanes along the entire corridor. These strategies allow the autonomous buses to maintain higher average speeds, reducing interference with general traffic.

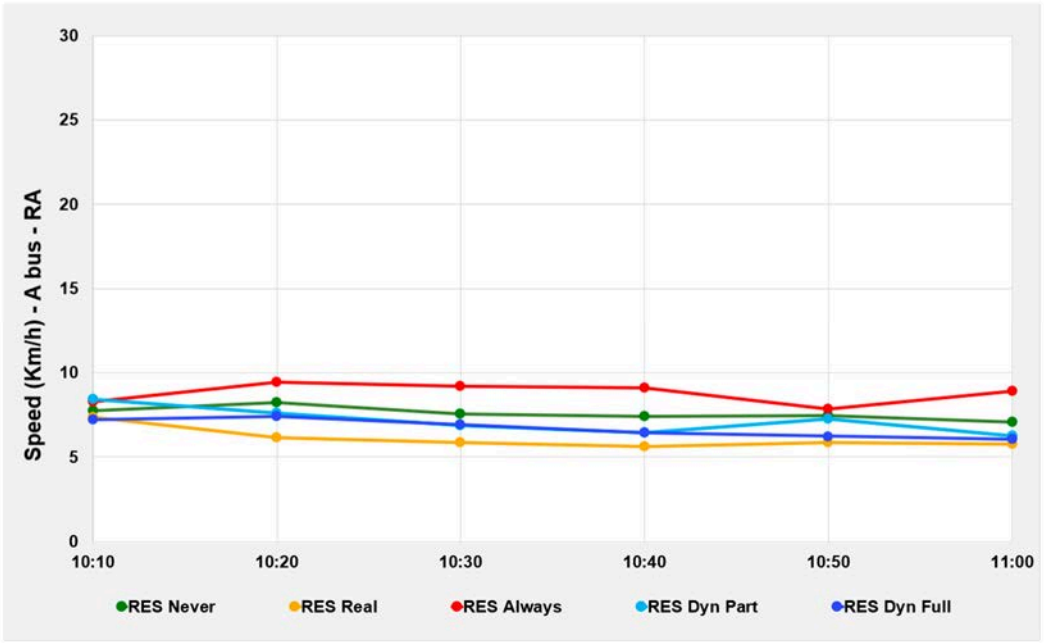


Figure 14. Speed of the autonomous bus during the simulation for each lane management scenario in the direction from roundabout R to intersection A, referred to as the local management approach.

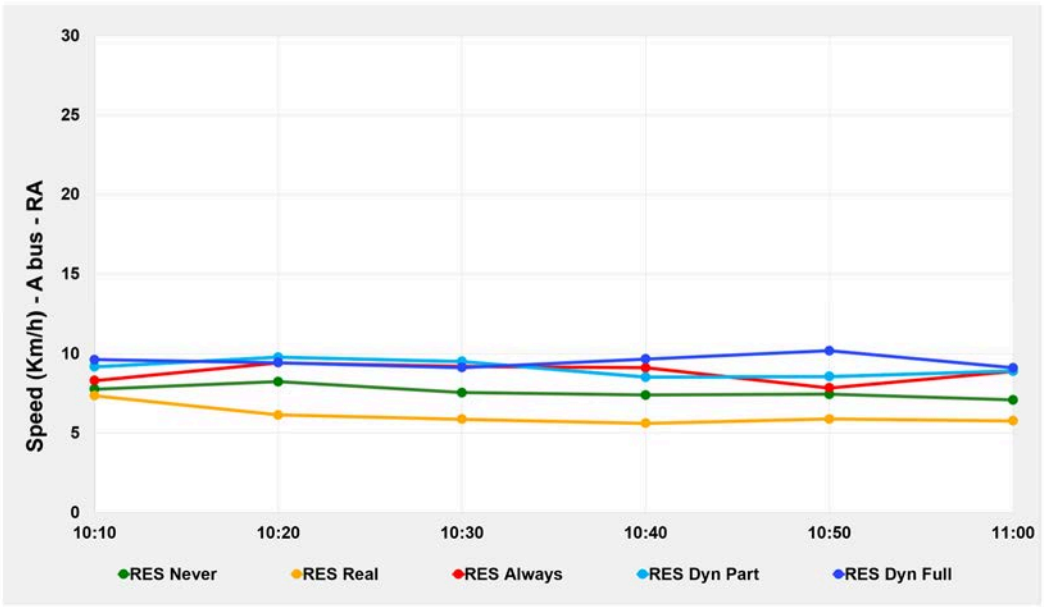


Figure 15. Speed of the autonomous bus during the simulation for each lane management scenario in the direction from roundabout R to intersection A, referred to as the arterial management approach.

Conversely, the "RES Real" and "RES Never" scenarios, characterised respectively by fragmented reservation and the absence of reserved lanes, show the lowest speed values, confirming that the lack of continuous reservation does not guarantee high operational performance for the service.

Analysing the speed in section 8, identified as the most critical section of the corridor, markedly lower speeds were observed. This section represents the first signalised intersection downstream of the roundabout, where traffic from the upstream unsignalised sections accumulates, leading to congestion and reduced operating speeds. Figure 16 shows the

performance of the five scenarios considering the implementation of the dynamic lane according to the local management methodology. In this case, the "RES Always" scenario proves to be the most advantageous configuration, ensuring the highest average speeds for the autonomous buses, while the scenarios characterised by dynamic reservation show lower speed values, highlighting the lesser effectiveness of the strategy when managed locally.

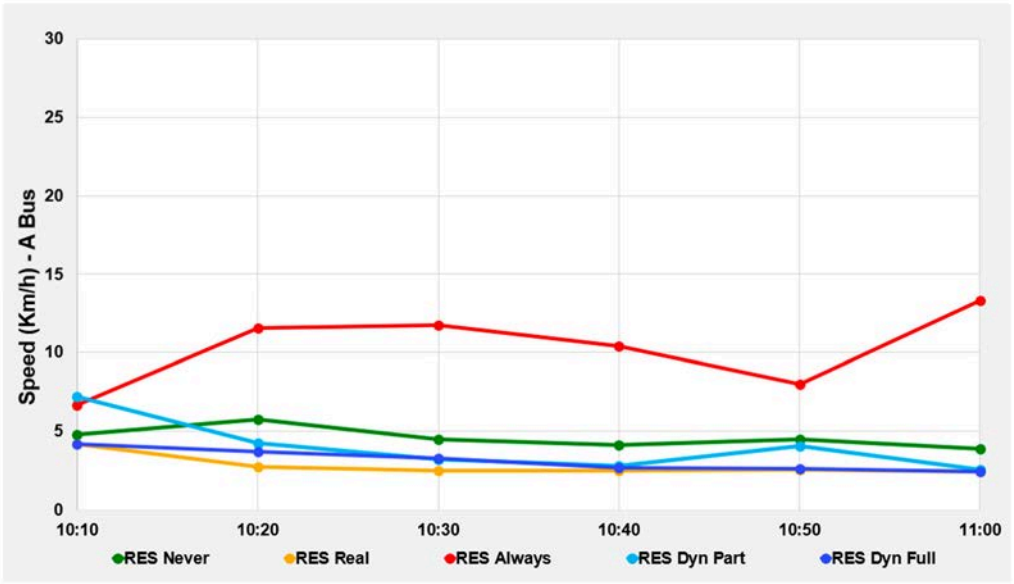


Figure 16. Speed of the autonomous bus during the simulation for each lane management scenario in section 8, referred to as the local management approach.

Consider Figure 17, however, regarding the implementation of the dynamic lane using the arterial management methodology; a different behaviour emerges. The dynamic scenarios show a significant increase in speeds, reaching values higher than those obtained in the "RES Always" scenario.

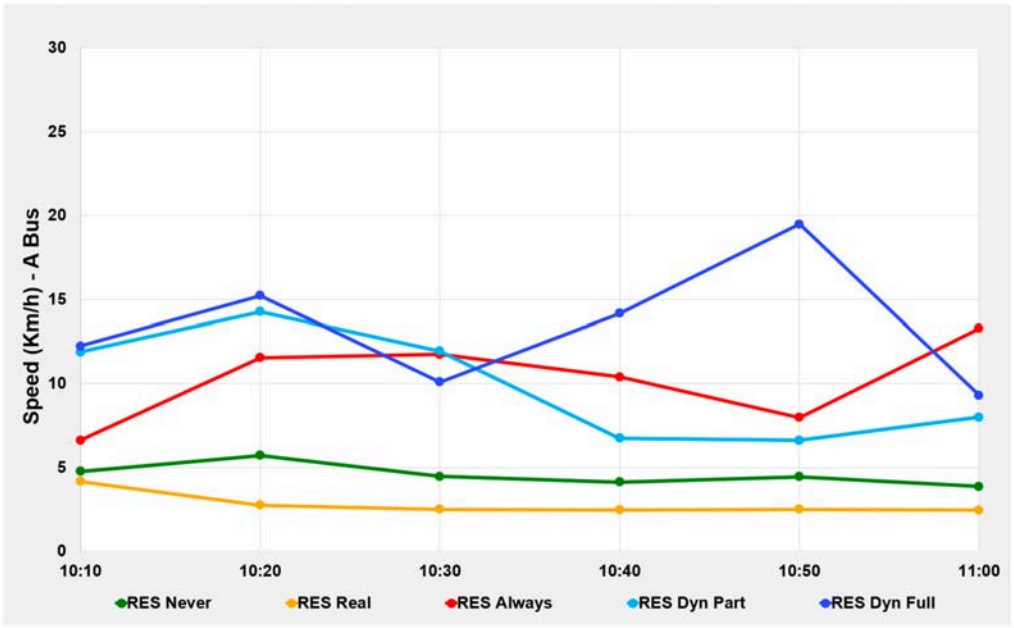


Figure 17. Speed of the autonomous bus during the simulation for each lane management scenario in section 8, referred to as the arterial management approach.

Comparing the "RES Never" scenario with the "RES DynFull" scenario, an increase in average speed of approximately 9 km/h is observed.

Furthermore, comparing the "RES DynFull" scenario of the case study with local management, with the corresponding scenario obtained using the arterial management methodology (Figures 16 and 17), the benefit resulting from the introduction of the new dynamic lane activation methodology allows for an increase in the average speed of the autonomous buses by 10.29 km/h compared to local management.

Also, in the most critical section of the corridor, the dynamic lane with the artery management allows for the full benefits of reservation, ensuring superior performance compared to both the absence of reservation and the configuration with a permanently dedicated lane.

4.2. Side Effect Results

This section analyses the effects of lane reservation strategies, especially the dynamic lane, identified as the most effective solution in the arterial configuration, on the performance of private traffic, to verify that the benefits gained for the public transport service using autonomous buses do not result in significant negative impacts on cars.

As section 8 proved to be the most critical and characterised by the greatest variations, the parameter of the number of lane changes was analysed to assess any effects induced by the different management strategies.

Table 9 shows the results, every ten minutes of the simulation period, for the five scenarios considered, obtained respectively using a local approach and an arterial-based approach.

Table 9. Mean number of lane changes in cars (#/veh), standard deviation and 95% confidence interval, every ten minutes during the simulation for each lane management scenario in section 8, referred to as local and arterial management approach.

	Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
		Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
Local	10:10:00	0.29	0.07	0.05	0.23	0.02	0.02	0.08	0.04	0.03	0.21	0.04	0.03	0.37	0.07	0.05
	10:20:00	0.19	0.09	0.07	0.18	0.04	0.03	0.10	0.03	0.02	0.23	0.04	0.03	0.21	0.05	0.04
	10:30:00	0.21	0.10	0.07	0.18	0.03	0.02	0.12	0.05	0.04	0.22	0.03	0.02	0.19	0.03	0.02
	10:40:00	0.14	0.06	0.04	0.15	0.03	0.02	0.15	0.03	0.02	0.23	0.03	0.02	0.21	0.05	0.03
	10:50:00	0.14	0.06	0.04	0.17	0.03	0.02	0.17	0.03	0.02	0.23	0.02	0.02	0.19	0.03	0.02
	11:00:00	0.12	0.04	0.03	0.18	0.03	0.02	0.17	0.03	0.02	0.23	0.03	0.02	0.21	0.06	0.04
Arterial	10:10:00	0.29	0.07	0.05	0.23	0.02	0.02	0.08	0.04	0.03	0.19	0.05	0.03	0.33	0.03	0.02
	10:20:00	0.19	0.09	0.07	0.18	0.04	0.03	0.10	0.03	0.02	0.24	0.04	0.03	0.22	0.06	0.04
	10:30:00	0.21	0.10	0.07	0.18	0.03	0.02	0.12	0.05	0.04	0.24	0.03	0.02	0.20	0.04	0.03
	10:40:00	0.14	0.06	0.04	0.15	0.03	0.02	0.15	0.03	0.02	0.24	0.03	0.02	0.22	0.04	0.03
	10:50:00	0.14	0.06	0.04	0.17	0.03	0.02	0.17	0.03	0.02	0.23	0.03	0.02	0.21	0.04	0.03
	11:00:00	0.12	0.04	0.03	0.18	0.03	0.02	0.17	0.03	0.02	0.25	0.03	0.02	0.20	0.05	0.03

In both cases, the trends are very similar and largely overlap, with no anomalies or significant increases in the number of lane changes observed between the different scenarios. This indicates that the introduction of reserved lanes, including dynamic ones, does not create any critical issues in terms of lane-changing manoeuvres.

As expected, the "RES Always" scenario involves the fewest lane changes, as the permanent reservation of a lane reduces the manoeuvring options available to cars. Furthermore, a comparison between the two dynamic lane activation strategies (local and arterial) shows that the adoption of a dynamic, arterial-based reservation strategy, whilst yielding significant benefits for autonomous buses, does not result in any appreciable changes in the behaviour of conventional vehicles in terms of lane changes. In fact, comparing the two "RES DynFull" configurations, only a slight increase of approximately 1.27% is observed

relative to the arterial-based approach, indicating that the variation in the average value over the simulation hour remains limited.

Therefore, the arterial approach improves the operating conditions for autonomous public transport without introducing any significant negative effects on conventional private traffic.

Figures 18 and 19 show the average speeds of cars travelling from intersection A to roundabout R. Specifically, Figure 18 relates to the dynamic scenarios implemented using a local-based approach, whilst Figure 19 presents the same scenarios using an arterial-based approach.

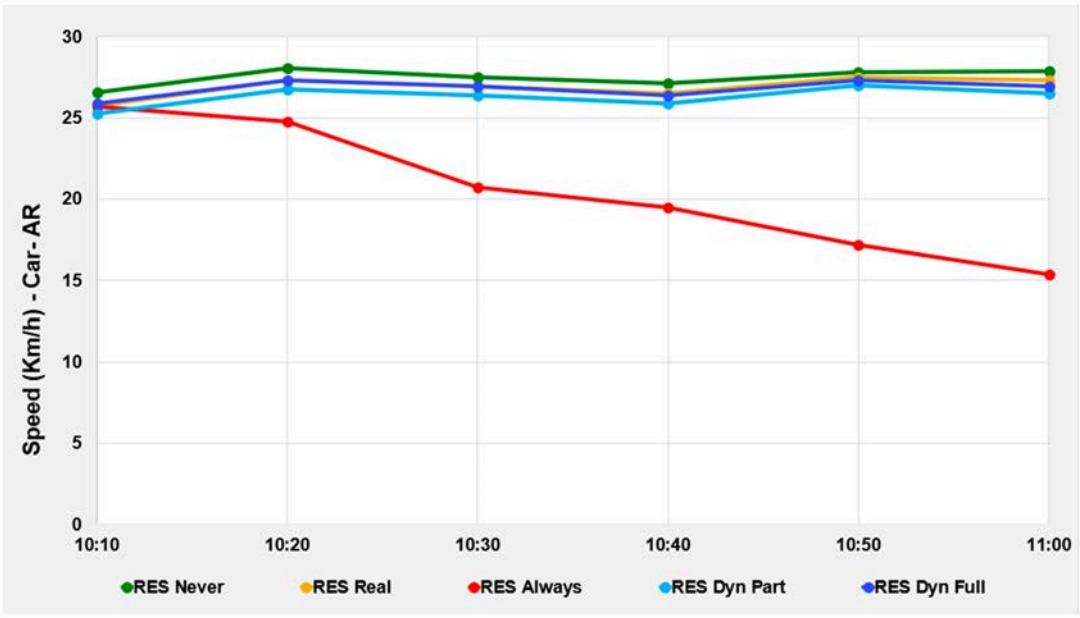


Figure 18. Speed of cars during the simulation for each lane management scenario in the direction from intersection A to roundabout R, referred to as the local management approach.

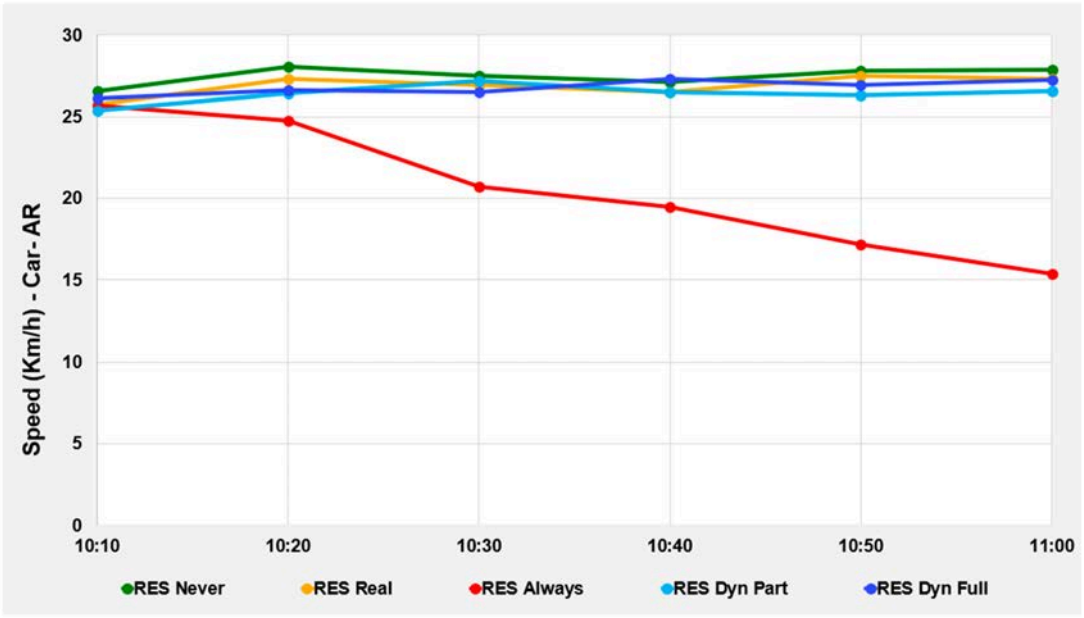


Figure 19. Speed of cars during the simulation for each lane management scenario in the direction from intersection A to roundabout R, referred to as the arterial management approach.

The most significant finding concerns the scenario with a permanently reserved lane, which proves to be the least efficient configuration in this direction, resulting in a marked

reduction in speeds throughout the entire simulation period. In fact, comparing the "RES DynFull" scenario with "RES Always" in Figure 19, an increase in average speeds of approximately 35.36% is observed. Although the permanently reserved strategy improves the operating conditions of autonomous buses operating as public transport, it has significant negative effects on traditional traffic.

Conversely, the dynamic reservation strategy allows speeds to be maintained at levels virtually identical to those observed in the other scenarios, thereby avoiding the marked decreases in speed associated with permanent lane reservation. These results highlight how dynamic reservation can facilitate the operation of autonomous public transport whilst limiting the impact on private traffic.

Similar considerations apply to the direction from R to A, analysed in Figures 20 and 21.

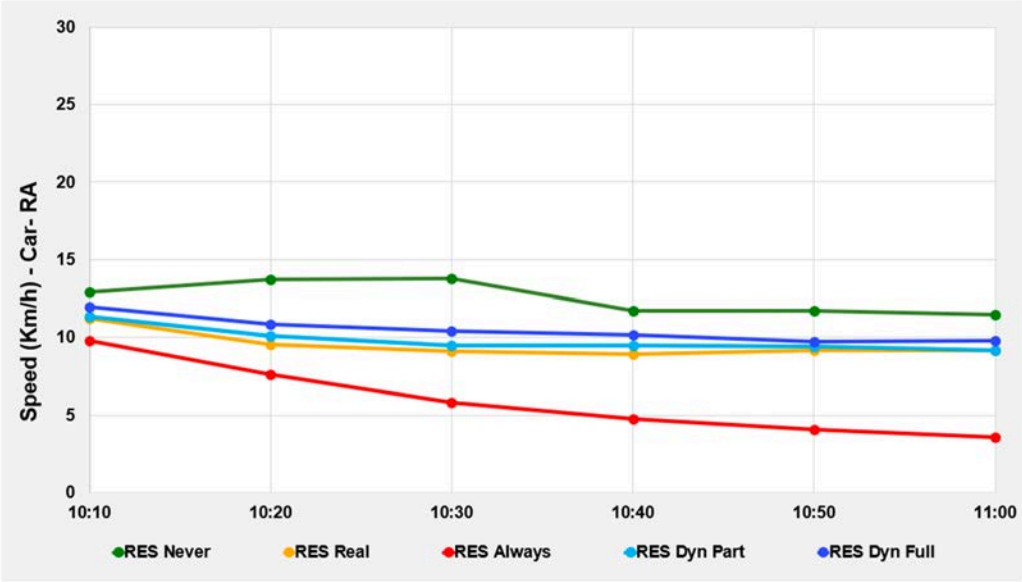


Figure 20. Speed of cars during the simulation for each lane management scenario in the direction from roundabout R to intersection A, referred to as the local management approach.

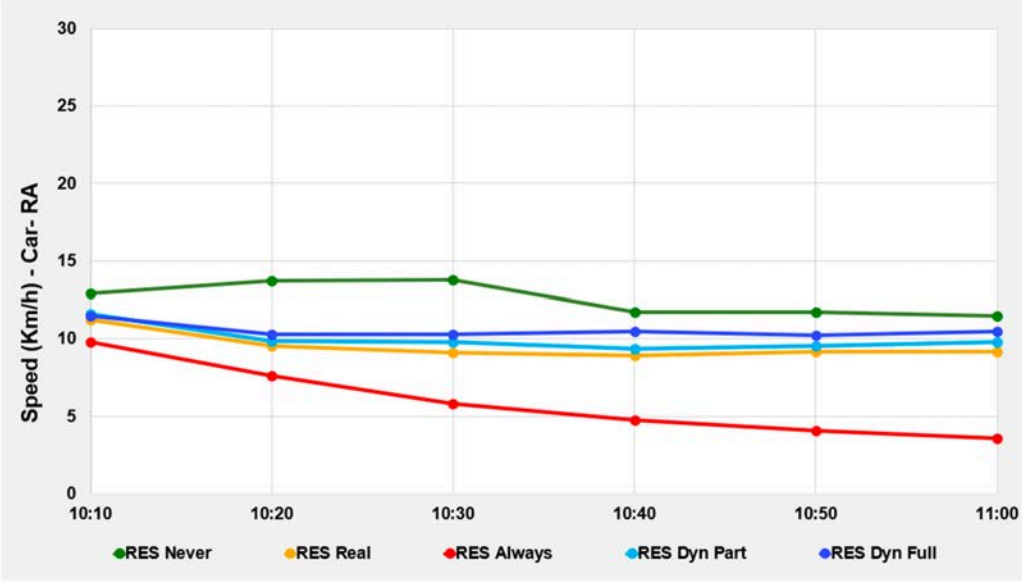


Figure 21. Speed of cars during the simulation for each lane management scenario in the direction from roundabout R to intersection A, referred to as the arterial management approach.

The "RES Always" scenario proves to be the least favourable for private traffic, resulting in a marked reduction in speeds. Conversely, "RES Never" represents the most efficient configuration for cars but serves as a baseline, as it does not guarantee a dedicated lane for autonomous buses operating as public transport.

Among the scenarios involving lane reservation, "RES DynFull" emerges as the most effective solution, as it provides a dedicated lane for autonomous buses whilst reducing the impact on conventional traffic. Comparing "RES DynFull" with "RES Never," Figure 20 shows a reduction of approximately 16.14%, whilst in Figure 21 the reduction is 15.45%. In this simulation, the arterial-based approach results in being not only more effective for the operation of autonomous buses but also having a less negative impact on conventional traffic, ensuring performance levels closer to those observed in the non-reserved scenario.

The use of continuous dynamic lane reservation along the corridor represents the best compromise between improving the autonomous service and reducing the effects on the rest of the network.

4.3. Sensitivity Analysis to Service Frequency Variations

Having identified the dynamic reservation strategy along the entire corridor (RES DynFull), with an arterial-based activation approach, as the most effective configuration both in terms of improving the operational performance of the autonomous buses and in reducing the impact on private traffic, a sensitivity analysis was carried out to assess the influence of service frequency on the strategy effectiveness. Starting from the baseline frequency of one A Bus every 10 min, two additional scenarios were then considered, with service frequencies of one bus every 8 or 6 min.

The analysis focused on two key indicators along the RA route, from the R roundabout towards the A intersection, previously identified as the most critical subpath: the A Bus travel time, to assess the performance of the autonomous public transport service, and private car speed, to analyse the effects on general traffic. The aim is to verify whether the benefits of full dynamic reservation are maintained as service frequency varies.

Figure 22 shows how the autonomous bus travel time varies during the simulation under the three different service frequencies considered. Overall, the variations are limited, with no substantial differences between the scenarios. Compared with the baseline frequency of one A Bus every 10 min, increasing the frequency to one bus every 8 min results in a 7.09% difference in travel time, while a frequency of one bus every 6 min leads to a difference of 9.80%. These results indicate that changes in service frequency have a limited impact on autonomous bus travel time, confirming the findings discussed previously.

Figure 23 shows the effect of changes in the frequency of the autonomous bus service on the speed of private vehicles. Overall, no substantial changes are observed. Compared with the baseline scenario, characterised by a frequency of one bus every 10 min, increasing the frequency to one bus every 8 min results in a 6.96% reduction in the average speed of private vehicles, whilst a frequency of one bus every 6 min leads to a reduction of 6.24%.

More detailed results on indicators, their standard deviation and 95% confidence interval, estimated every ten minutes during the simulation, are reported in Appendix A.

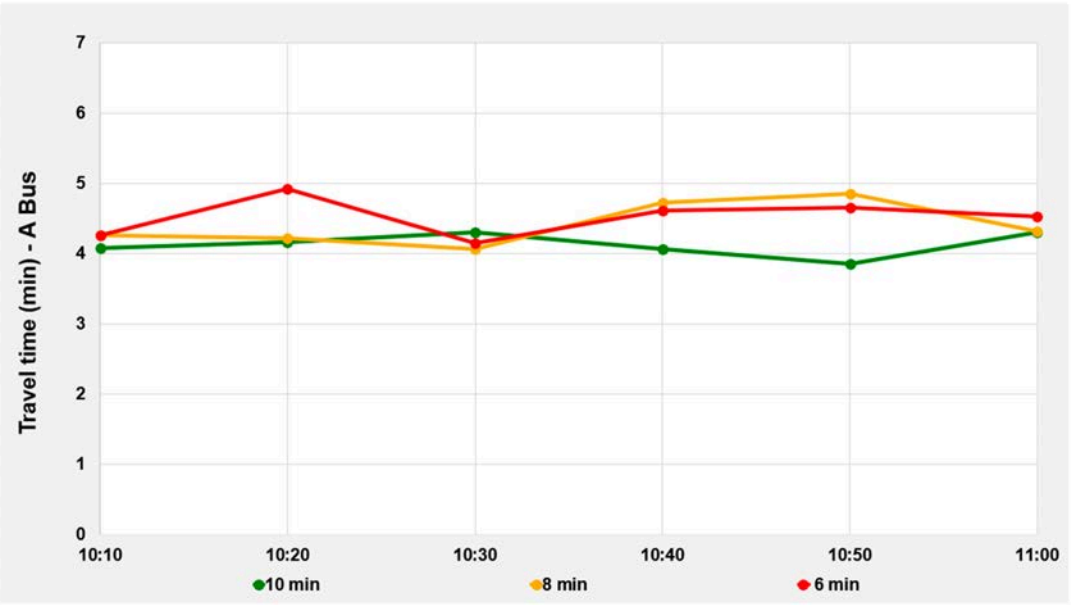


Figure 22. Travel time of A Bus with three A Bus frequencies during the simulation for "RES DynFull" scenario in the direction from roundabout R to intersection A, referred to as the arterial management approach.

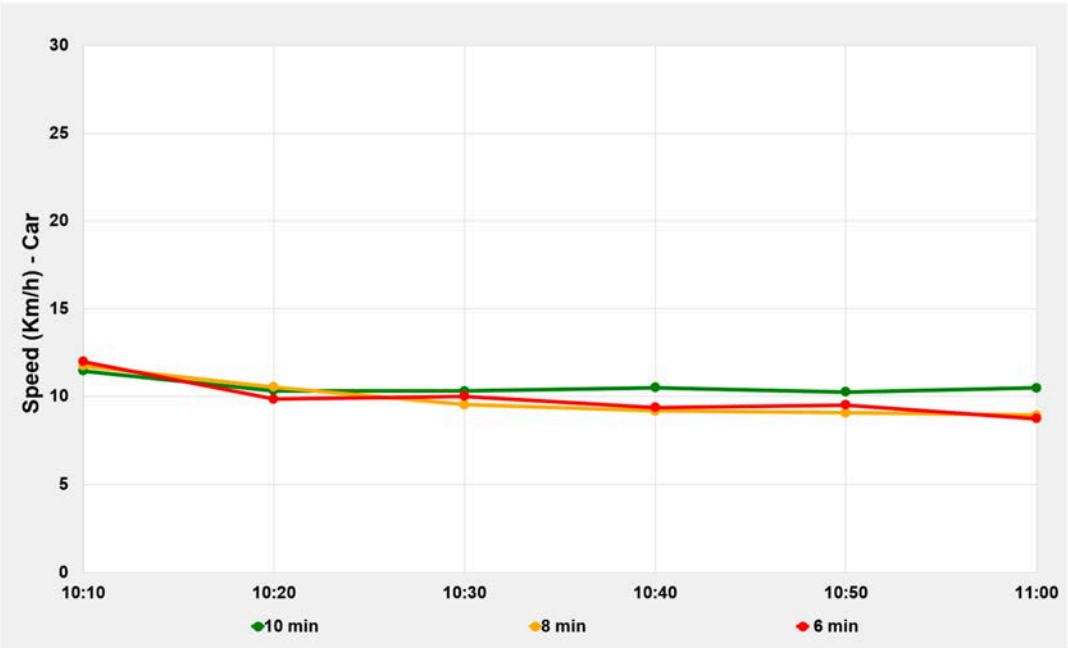


Figure 23. Speed of cars with three A Bus frequencies during the simulation for the "RES DynFull" scenario in the direction from roundabout R to intersection A, referred to as the arterial management approach.

5. Conclusions

Lane management strategies for autonomous public transport are evaluated in simulation by implementing in a virtual environment the bus detection and lane activation logics, aiming to compare different options. Static and dynamic lane reservation strategies are simulated across different corridor configurations, including single-strategy scenarios, combined approaches, and no-reservation baseline conditions.

In each situation, buses and other vehicles are simulated using a microscopic approach in which each vehicle state, including its position, speed and lane, is updated on a sub-second basis, generating vehicle interactions along the road network.

On the basis of the experiments performed, the dynamic lane reservation applied along a corridor emerged as the most effective strategy among those tested, improving the public service operated by autonomous buses, whilst limiting the impacts on conventional traffic. In particular, dynamic reservation of the entire corridor ("RES DynFull" scenario) enables the autonomous buses to achieve travel and stop times shorter than those achieved with a permanently reserved lane configuration, whilst mitigating the negative impacts on private vehicles.

Indeed, the fixed lane reservation strategy was found to cause significant reductions in the speeds of traditional vehicles, highlighting its detrimental impact on private traffic and the excessive penalties imposed on non-prioritised users.

Furthermore, the benefits associated with dynamic lanes are particularly evident in the direction with higher traffic levels, where the activation criteria associated with the artery-based methodology differ from those adopted in the local management approach. In this case, the artery-based strategy offers significant advantages for the autonomous buses, reducing the travel time required to traverse the corridor by 20.73% compared to the baseline non-reserved scenario and stop time by 47.52%.

Therefore, dynamic reservation of the entire corridor, as proposed and implemented in the traffic microsimulator, not only guarantees the same benefits associated with a fully dedicated infrastructure, which provides a protected and uninterrupted route for the autonomous buses, but also improves the overall performance of the network by limiting the disadvantages experienced by private vehicles.

Furthermore, an assessment of different service frequencies for autonomous buses confirms that there are no substantial variations in the main indicators, showing only a negligible impact on both the travel times of autonomous buses and the speed of private vehicles.

The main limitations of this study may be related to the generalisation of the results obtained for this case study, which refers to a specific road network configuration, traffic light control and traffic demand pattern. However, the proposed method based on simulation can be easily transferred to other cases to evaluate whether, in specific conditions, a reserved lane approach can be useful or even unnecessary. Indeed, road configuration and demand level, jointly with traffic light control, can play a significant role in generating long queues at approaches to intersections to justify bus lane reservation strategies.

This study represents a preliminary assessment of lane management strategies for autonomous public transport along urban arterials.

Future research could assess the robustness of the proposed strategies under different traffic demand levels and patterns, as well as different autonomous bus operating speeds, including less conservative driving behaviours. The analysis could also incorporate a broader set of performance indicators to provide a more comprehensive assessment of the strategies' impacts on overall network performance.

Further studies can then be performed to evaluate different lane activation and deactivation latencies, considering the requirements of potential real-world implementation and the characteristics of the adopted detection technology, whether infrastructure-based, using roadside sensors, or vehicle-based, relying on onboard devices and positioning technologies.

Author Contributions: Conceptualisation, A.C., F.D., B.C., and A.B.; methodology, A.C., F.D., B.C., and A.B.; software, A.C.; validation, A.C., F.D., and B.C.; formal analysis, A.C.; data curation, A.C.; writing—original draft preparation, A.C. and A.B.; writing—review and editing, A.C., F.D., B.C., and A.B.; visualisation, A.C. and F.D.; supervision, F.D. and B.C.; project administration, F.D. All authors have read and agreed to the published version of the manuscript.

Funding: The PhD of the author Alina Cavallero was partially funded by the project PNRR-NGEU through the MUR—CUP n° E12B22000530006DM 352/2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: The authors would like to thank Irizar e-mobility for the information shared.

Conflicts of Interest: Author Alberto Bellini was employed by the company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Data Tables

Table A1. Mean travel time of A Bus (s), standard deviation and 95% confidence interval, estimated for every lane management scenario along the subpath RA, referred to as the local and arterial management approach.

Approach	RES Never			RES Real			RES Always			RES Dyn Part			RES Dyn Full		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
Local	311.51	30.81	22.04	389.24	17.63	12.61	268.03	16.59	11.87	332.36	19.25	13.77	352.28	27.03	19.34
Arterial	311.51	30.81	22.04	389.24	17.63	12.61	268.03	16.59	11.87	260.26	15.61	11.17	247.63	12.14	8.68

Table A2. Mean stop time of A Bus (s), standard deviation and 95% confidence interval, estimated for every lane management scenario along the subpath RA, referred to as the local and arterial management approach.

Approach	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
Local	119.71	23.99	17.16	186.74	14.82	10.60	83.39	16.87	12.07	148.13	19.99	14.30	174.23	27.22	19.48
Arterial	119.71	23.99	17.16	186.74	14.82	10.60	83.39	16.87	12.07	75.39	15.35	10.98	62.83	12.24	8.76

Table A3. Mean speed of A Bus (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along the subpath RA, referred to as the local management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	7.76	1.22	0.87	7.35	0.30	0.21	8.30	1.34	0.96	8.41	1.69	1.21	7.24	1.57	1.13
10:20:00	8.24	1.47	1.05	6.14	0.84	0.60	9.43	1.17	0.83	7.63	1.63	1.17	7.41	1.39	0.99
10:30:00	7.55	2.03	1.45	5.87	0.55	0.39	9.18	1.25	0.89	6.86	1.21	0.87	6.95	1.20	0.86
10:40:00	7.39	0.20	0.15	5.61	0.52	0.37	9.11	1.18	0.84	6.45	0.85	0.60	6.43	0.88	0.63
10:50:00	7.44	1.46	1.05	5.89	0.63	0.45	7.83	1.31	0.94	7.26	1.55	1.11	6.23	0.86	0.62
11:00:00	7.09	1.21	0.87	5.77	0.53	0.38	8.90	1.22	0.87	6.23	1.13	0.81	6.07	0.79	0.56

Table A4. Mean speed of A Bus (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along the subpath RA, referred to as the arterial management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	7.76	1.22	0.87	7.35	0.30	0.21	8.30	1.34	0.96	9.17	1.57	1.12	9.62	1.16	0.83
10:20:00	8.24	1.47	1.05	6.14	0.84	0.60	9.43	1.17	0.83	9.78	0.86	0.61	9.43	1.08	0.78
10:30:00	7.55	2.03	1.45	5.87	0.55	0.39	9.18	1.25	0.89	9.51	1.07	0.77	9.12	1.25	0.89
10:40:00	7.39	0.20	0.15	5.61	0.52	0.37	9.11	1.18	0.84	8.52	1.44	1.03	9.66	0.89	0.64

Table A4. *Cont.*

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:50:00	7.44	1.46	1.05	5.89	0.63	0.45	7.83	1.31	0.94	8.55	1.59	1.14	10.18	0.34	0.24
11:00:00	7.09	1.21	0.87	5.77	0.53	0.38	8.90	1.22	0.87	8.90	1.52	1.08	9.11	1.24	0.89

Table A5. Mean speed of A Bus (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along section 8, referred to as the local management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	4.77	5.28	3.78	4.17	0.63	0.45	6.63	7.92	5.66	7.21	7.51	5.37	4.19	6.80	4.87
10:20:00	5.73	5.54	3.96	2.75	0.79	0.56	11.55	6.60	4.72	4.23	6.51	4.66	3.72	5.68	4.06
10:30:00	4.48	7.33	5.24	2.51	0.53	0.38	11.74	6.52	4.66	3.23	3.64	2.60	3.26	5.36	3.83
10:40:00	4.13	0.34	0.24	2.48	0.57	0.41	10.40	6.61	4.73	2.82	0.86	0.62	2.65	0.79	0.56
10:50:00	4.46	5.31	3.80	2.52	0.51	0.36	7.98	7.35	5.26	4.03	5.99	4.28	2.59	0.70	0.50
11:00:00	3.87	4.84	3.46	2.45	0.33	0.23	13.28	6.13	4.39	2.52	0.98	0.70	2.41	0.78	0.55

Table A6. Mean speed of A Bus (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along section 8, referred to as the arterial management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	4.77	5.28	3.78	4.17	0.63	0.45	6.63	7.92	5.66	11.89	6.49	4.65	12.24	6.39	4.57
10:20:00	5.73	5.54	3.96	2.75	0.79	0.56	11.55	6.60	4.72	14.27	5.04	3.61	15.23	4.66	3.33
10:30:00	4.48	7.33	5.24	2.51	0.53	0.38	11.74	6.52	4.66	11.95	6.08	4.35	10.10	7.35	5.26
10:40:00	4.13	0.34	0.24	2.48	0.57	0.41	10.40	6.61	4.73	6.75	7.85	5.62	14.17	5.00	3.58
10:50:00	4.46	5.31	3.80	2.52	0.51	0.36	7.98	7.35	5.26	6.63	8.20	5.86	19.48	1.24	0.88
11:00:00	3.87	4.84	3.46	2.45	0.33	0.23	13.28	6.13	4.39	8.01	7.77	5.56	9.32	7.44	5.32

Table A7. Mean speed of cars (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along the subpath AR, referred to as the local management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	26.54	1.12	0.80	25.77	0.82	0.59	25.67	0.48	0.35	25.28	0.84	0.60	25.89	0.93	0.66
10:20:00	28.04	1.89	1.35	27.28	1.92	1.37	24.75	0.94	0.67	26.78	1.80	1.28	27.31	1.86	1.33
10:30:00	27.48	1.16	0.83	26.96	1.06	0.76	20.69	2.75	1.97	26.37	0.95	0.68	26.96	0.84	0.60
10:40:00	27.14	0.85	0.61	26.49	0.99	0.71	19.44	2.78	1.99	25.90	1.00	0.71	26.40	0.95	0.68
10:50:00	27.82	1.37	0.98	27.49	1.23	0.88	17.18	2.69	1.92	27.02	1.12	0.80	27.34	1.16	0.83
11:00:00	27.87	1.34	0.96	27.31	1.51	1.08	15.38	2.65	1.90	26.51	1.32	0.94	26.94	1.28	0.92

Table A8. Mean speed of cars (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along the subpath AR, referred to as the arterial management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	26.54	1.12	0.80	25.77	0.82	0.59	25.67	0.48	0.35	25.41	0.49	0.35	26.16	1.09	0.78
10:20:00	28.04	1.89	1.35	27.28	1.92	1.37	24.75	0.94	0.67	26.45	0.89	0.63	26.63	1.00	0.72
10:30:00	27.48	1.16	0.83	26.96	1.06	0.76	20.69	2.75	1.97	27.17	1.76	1.26	26.49	0.99	0.71
10:40:00	27.14	0.85	0.61	26.49	0.99	0.71	19.44	2.78	1.99	26.49	0.80	0.57	27.32	1.35	0.97
10:50:00	27.82	1.37	0.98	27.49	1.23	0.88	17.18	2.69	1.92	26.31	0.80	0.57	26.97	0.92	0.66
11:00:00	27.87	1.34	0.96	27.31	1.51	1.08	15.38	2.65	1.90	26.56	1.17	0.83	27.23	1.94	1.39

Table A9. Mean speed of cars (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along the subpath RA, referred to as the local management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	12.93	1.70	1.21	11.19	0.70	0.50	9.82	1.05	0.75	11.32	0.49	0.35	11.99	1.23	0.88
10:20:00	13.68	2.52	1.80	9.56	0.44	0.31	7.59	1.25	0.89	10.12	0.41	0.30	10.86	1.59	1.14
10:30:00	13.79	3.47	2.49	9.10	0.52	0.37	5.79	1.10	0.79	9.49	0.77	0.55	10.44	1.84	1.32
10:40:00	11.71	2.39	1.71	8.91	0.30	0.22	4.77	1.35	0.97	9.46	0.77	0.55	10.18	1.27	0.91
10:50:00	11.70	2.25	1.61	9.15	0.38	0.27	4.05	1.26	0.90	9.39	0.55	0.39	9.73	0.54	0.38
11:00:00	11.48	2.05	1.46	9.15	0.18	0.13	3.57	1.36	0.97	9.19	0.82	0.59	9.78	0.63	0.45

Table A10. Mean speed of cars (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for every lane management scenario along the subpath RA, referred to as the arterial management approach.

Time	RES Never			RES Real			RES Always			RES DynPart			RES DynFull		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	12.93	1.70	1.21	11.19	0.70	0.50	9.82	1.05	0.75	11.57	0.82	0.59	11.45	1.04	0.74
10:20:00	13.68	2.52	1.80	9.56	0.44	0.31	7.59	1.25	0.89	9.86	0.90	0.64	10.32	1.58	1.13
10:30:00	13.79	3.47	2.49	9.10	0.52	0.37	5.79	1.10	0.79	9.80	0.89	0.63	10.30	1.15	0.82
10:40:00	11.71	2.39	1.71	8.91	0.30	0.22	4.77	1.35	0.97	9.35	0.60	0.43	10.50	1.07	0.77
10:50:00	11.70	2.25	1.61	9.15	0.38	0.27	4.05	1.26	0.90	9.56	0.46	0.33	10.26	1.60	1.15
11:00:00	11.48	2.05	1.46	9.15	0.18	0.13	3.57	1.36	0.97	9.77	0.88	0.63	10.48	1.60	1.15

Table A11. Mean travel time of A Bus (s), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for the "RES DynFull" scenario along the subpath RA, referred to as the arterial management approach.

Time	10 min			8 min			6 min		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	244.66	34.92	24.98	255.35	41.14	29.43	255.53	41.03	29.35
10:20:00	249.73	34.09	24.39	253.21	37.44	26.78	295.12	21.50	15.38
10:30:00	258.18	38.87	27.81	243.47	30.46	21.79	249.20	32.22	23.05
10:40:00	243.61	28.36	20.29	283.44	24.02	17.18	277.01	25.45	18.20
10:50:00	231.20	7.60	5.44	291.19	40.18	28.74	279.06	20.00	14.31
11:00:00	258.41	38.93	27.85	258.93	38.53	27.56	272.03	51.21	36.64

Table A12. Mean speed of cars (Km/h), standard deviation and 95% confidence interval, estimated every ten minutes during the simulation for the "RES DynFull" scenario along the subpath RA, referred to as the arterial management approach.

Time	10 min			8 min			6 min		
	Mean	SD	CI	Mean	SD	CI	Mean	SD	CI
10:10:00	11.45	1.04	0.74	11.74	0.74	0.53	11.98	0.61	0.43
10:20:00	10.32	1.58	1.13	10.54	0.59	0.42	9.84	0.74	0.53
10:30:00	10.30	1.15	0.82	9.53	1.10	0.79	10.01	1.35	0.97
10:40:00	10.50	1.07	0.77	9.18	1.09	0.78	9.37	1.33	0.95
10:50:00	10.26	1.60	1.15	9.06	1.05	0.75	9.52	1.66	1.19
11:00:00	10.48	1.60	1.15	8.93	0.97	0.70	8.73	1.71	1.22

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